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Short Communication

Multi-segment foot mobility in a hinged ankle-foot orthosis: the effect of rotation axis position

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ABSTRACT

Hinged ankle-foot orthoses are prescribed routinely for the treatment of ankle joint deficits, despite the conflicting outcomes and the little evidence on their functional efficacy. In particular, the axis of rotation of the hinge is positioned disregarding the physiological position and orientation. A multi-segment model was utilized to assess in vivo the effect of different positions for this axis on the kinematics of foot joints.

A special custom-made hinged orthosis was manufactured via standard procedures for a young healthy volunteer. Four locations for the mechanical axis were obtained by a number of holes where two nuts and bolts were inserted to form the hinge: a standard position well above the malleoli, at the level of the medial malleolus, at the level of the lateral malleolus, and the physiological between the two malleoli. The shank and foot were instrumented with 15 reflective markers according to a standard protocol, and level walking was collected barefoot and with the orthosis in the four mechanical conditions.

The spatio-temporal parameters observed in the physiological axis condition were the closest to normal barefoot walking. As expected, ankle joint rotation was limited to the sagittal plane. When the physiological axis was in place, rotations of the ankle out-of-sagittal planes, and of all other foot joints in the three anatomical planes, were found to be those most similar to the natural barefoot condition.

These preliminary measures of intersegmental kinematics in a foot within an ankle-foot orthosis showed that only a physiological location for the ankle mechanical hinge can result in natural motion at the remaining joints and planes.

1. Introduction

Hinged ankle-foot orthoses (HAFO) are prescribed for the treatment of ankle joint deficits from neurological and orthopaedic disorders. HAFO are intended to compensate for weakness, but mainly to limit three-dimensional ankle mobility to the sagittal plane only. Quantitative assessment of their functional efficacy is still very limited, with conflicting outcomes which challenge current treatment algorithms [1]. The overall effect on activity level, or on the whole gait performance [2] as well as mechanical evidence of the function of the orthoses themselves [3–5] has been reported but there is very little evidence on the kinematic effects on the foot intersegmental joints.

In routine custom-made manufacturing of HAFO, the mechanical hinge is positioned with a medio-lateral orientation, i.e. orthogonal to the sagittal plane of the shank, and a few centimetres above the malleoli to avoid possible interference with the shoes. This location is far from the physiological position and orientation for the ankle axis of rotation, which is known to be between the apex of the medial (MM) and lateral malleolus (LM), therefore inclined both in the frontal and transverse planes. Mobility at the ankle complex and at the other main foot joints would potentially benefit from a more physiological location of the hinge, which guides the motion of the foot plate with respect to the calf shell. The importance of joint alignment has been recently demonstrated, but only by mathematical modelling [3] and in vitro experiments [4]. Current multi-segment kinematic models provide accurate foot joint motion in non-invasive experiments, compatible also with the presence of orthoses.

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The aim of this study is to assess in vivo the effect of the position of the mechanical hinge in unlocked HAFO on intersegmental foot kinematics.

2. Materials and methods

A healthy subject (woman, 25 years old), free from any foot and ankle pathology, volunteered for the data collection. A special custom-made HAFO (Biotecnica s.r.l., Bologna, Italy) was manufactured for the subject's right leg via standard procedures. These involved producing a lower leg plaster cast and its manual stylization, moulding of relevant thermoplastics material, testing and final refining over the cast and on the subject. In this HAFO (Fig. 1), four possible locations for its axis were established by drilling three holes each in the area of the malleoli, where two nuts and bolts were each time inserted to create the mechanical hinge. The final plastic footplate and calf shell were trimmed to avoid impingement with the skin markers. The physiological intermalleolar location for the mechanical hinge axis (MM-LM) was arranged, though its physiological inclination was sought only in the frontal plane. Exact medio-lateral orientations were also analyzed, in three different locations on the calf shell: in the standard position well above the malleoli (STD), and at the level of MM and LM.

The leg of the volunteer was instrumented with fifteen reflective markers (10 mm diameter), according to a standard protocol [6]. Foot joints kinematics were first recorded during natural barefoot walking, without orthosis. Subsequently, the four different axis configurations were tested and collected, after corresponding setting of the mechanical hinge and a period of familiarization with the HAFO. A comfortable flat-soled shoe was worn on the left side. For each axis configuration, a static position in double-leg posture, and ten correct walking trials at self-selected speed were collected. An eight-camera motion capture system (Vicon Motion Systems Ltd., Oxford, UK) and two force plates (Kistler Instrument AG, Switzerland) were used to collect 100 Hz kinematics and spatio-temporal gait data. Force plates and motion of the calcaneus marker were used to identify the gait cycle between the two heel strikes.

Intersegmental rotations were calculated in the sagittal, frontal and transverse planes, respectively dorsi-/plantar-flexion (Do/Pl), abduction/adduction (Abd/Add) and eversion/inversion (Eve/Inv), and for the joint between the shank and the calcaneus (Sha-Cal joint), the calcaneus and the mid-foot (Cal-Mid), the mid-foot and the metatarsus (Mid-Met), the metatarsus and the calcaneus (Cal-Met), and also between the shank and the entire foot (Sha-Foo).

3. Results

The spatio-temporal parameters observed in the MM-LM condition were the closest to normal barefoot walking (Table 1). Those obtained in walking trials wearing the HAFO were all significantly different, i.e. *t*-test, from those recorded during barefoot walking, apart from the stride length in MM-LM condition.

High inter-trial consistency was observed. In the barefoot condition, the mean standard deviation of each joint rotation in each plane over the gait cycle was found smaller than 1.4° across the 10 repetitions; in the STD HAFO condition this was smaller than 1.7° in the sagittal plane, and smaller than 0.9° in the frontal and transverse planes. Therefore the mean patterns over the trials are here discussed. As expected, in general, the motion of the foot with respect to the shank (Sha-Foo) in out-of-sagittal planes was found to be limited with the HAFO with respect to the barefoot condition: in the frontal plane, the natural range of 20° reduced to about 6°; in the transverse plane, the natural range of 18° reduced to less than 5° in all four HAFO conditions. In the sagittal plane, a little larger range of motion in stance and a smaller range in swing were observed for the HAFO conditions with respect to the barefoot one.

For a clearer interpretation of the results, the absolute difference between every HAFO condition and barefoot was

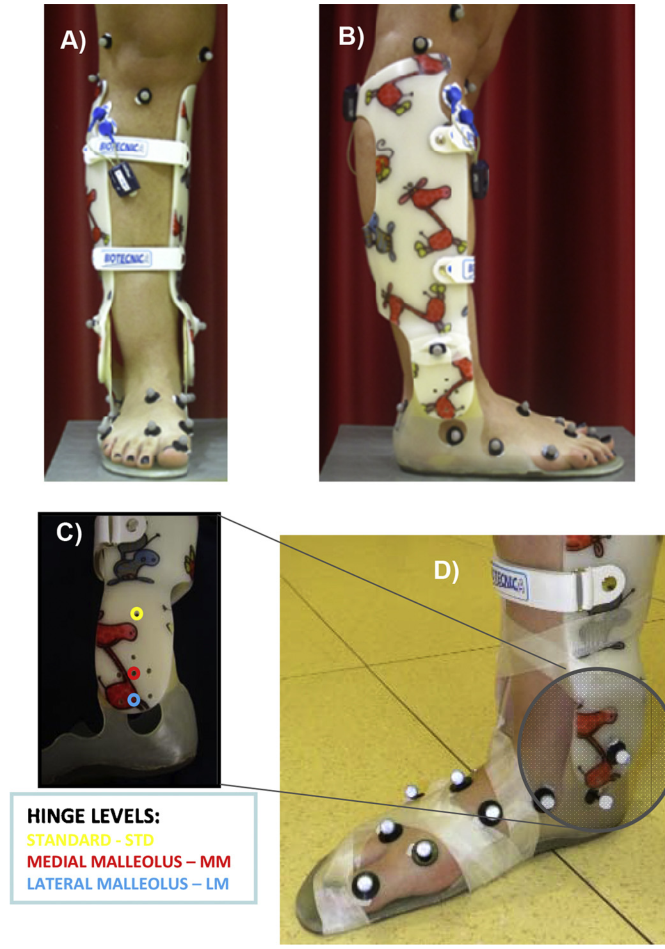

Fig. 1. Pictures of the final custom-made HAFO, with the instrumented leg. (A) Front view. (B) Lateral view. (C) The three main holes on the medial side, for the nuts and bolts to be arranged to form the mechanical hinge axis of flexion (corresponding holes are on the lateral side, at the same level). (D) Close up of the foot within the footplate of the HAFO; hinge markers are here on the MM side.

Table 1
Mean ± st.dev. of the main spatio-temporal parameters over the ten repetitions, for the barefoot and the four different HAFO conditions (five columns: barefoot; standard position well above the malleoli – STD; at the level of MM; at the level of LM); physiological location through inclination MM-LM).

	Barefoot	STD	MM	LM	MM-LM
Stance time (%)	60.3 ± 1.0	63.2 ± 2.3	63.6 ± 1.3	63.5 ± 0.7	63.3 ± 0.7
Swing time (%)	39.7 ± 1.0	36.8 ± 2.3	36.4 ± 1.3	36.5 ± 0.7	36.7 ± 0.7
Stride length (cm)	77.1 ± 1.4	63.9 ± 2.8	71.7 ± 1.0	74.8 ± 1.5	77.0 ± 1.5*
Cadence (step/min)	56.7 ± 1.1	47.3 ± 2.0	53.4 ± 1.3	52.4 ± 1.2	54.0 ± 1.0
Speed (cm/s)	117.4 ± 2.8	81.0 ± 4.0	102.7 ± 4.0	105.1 ± 2.0	111.5 ± 3.4

* $p > 0.05$ with respect to the barefoot condition.