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One- and multi-segment foot models lead to opposite results on ankle joint kinematics during gait: Implications for clinical assessment

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ABSTRACT

Background: Biomechanical models representing the foot as a single rigid segment are commonly used in clinical or sport evaluations. However, neglecting internal foot movements could lead to significant inaccuracies on ankle joint kinematics. The present study proposed an assessment of 3D ankle kinematic outputs using two distinct biomechanical models and their application in the clinical flat foot case.
Methods: Results of the Plug in Gait (one segment foot model) and the Oxford Foot Model (multisegment foot model) were compared for normal children (9 participants) and flat feet children (9 participants). Repeated measures of Analysis of Variance have been performed to assess the *Foot model* and *Group* effects on ankle joint kinematics.
Findings: Significant differences were observed between the two models for each group all along the gait cycle. In particular for the flat feet group, opposite results between the Oxford Foot Model and the Plug in Gait were revealed at heelstrike, with the Plug in Gait showing a 4.7° ankle dorsal flexion and 2.7° varus where the Oxford Foot Model showed a 4.8° ankle plantar flexion and 1.6° valgus.
Interpretation: Ankle joint kinematics of the flat feet group was more affected by foot modeling than normal group. Foot modeling appeared to have a strong influence on resulting ankle kinematics. Moreover, our findings showed that this influence could vary depending on the population. Studies involving ankle joint kinematic assessment should take foot modeling with caution.

1. Introduction

The foot is a complex anatomical structure composed of many articulated segments that allow a wide variety of movements. Modeling the foot is consequently known as a key issue in gait analysis (Deschamps et al., 2011). Classical biomechanical models, such as the Plug in Gait (PIG) (Kadaba et al., 1990), consider the foot as a mono-segmental unit linked to the tibia by the ankle joint, thus neglecting internal foot movements. Numerous multisegment foot models have been developed to overcome this limitation (Deschamps et al., 2011; Dixon et al., 2012; Baker and Robb, 2006). Among them, the Oxford Foot Model (OFM) represents the foot as three segments which are the rearfoot (calcaneum), the forefoot (metatarsal segments) and the hallux. This model is aimed at better transcribing the foot anatomy. The OFM repeatability has been validated for adults and children (Curtis et al., 2009; Stebbins et al., 2006). These multi-segment foot models undoubtedly made a consequent knowledge emerge on internal foot movements.

Even with the known limitations in mind, such as the drastic reduction of the anatomical degrees of freedom when using a mono-segment foot model, the ankle joint kinematics and kinetics computed by one-segment foot models are still used daily for clinical or sport lower limb evaluations (Moore and Dixon, 2014; Pasini Neto et al., 2012; Böhm and Döderlein, 2012; Thompson et al., 2014). As kinematics are input data for inverse dynamics computations, it is of prime interest to understand the implications of using different foot kinematic models and their influences when assessing lower limb function (Dixon et al., 2012).

Furthermore, it could be important to analyze whether the differences in ankle joint kinematics observed between two kinematic models are consistent even when the foot is highly distorted, especially in sport and clinical evaluations. Indeed in these situations, more strain can be generated within the foot and lead to a different influence of the foot model on ankle kinematics. Together with typically developing children, this study assessed idiopathic pediatric flat feet gait, a common clinical deformation (Mosca, 2010), to investigate this issue. Indeed, children displaying flexible flat feet are often a source of concern for parents and lead to a large number of orthopedic consultations (Pfeiffer et al., 2006),

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being conducted using clinical gait analysis techniques. This deformation is characterized by a flattening medial longitudinal arch associated with a rearfoot valgus exceeding 4° in weight bearing position. This particular situation of foot distortion can enhance the weakness of one segment foot models for gait analyses.

The aim of this study was to assess the differences in the ankle joint kinematics computed by the PIG and the OFM models, and to compare these differences between flexible flat feet children (*flat* group) and normal children (*normal* group). We hypothesized that 1) differences between the OFM and the PIG models will emerge in the ankle joint kinematics for normal children, 2) the flat feet group will show more significant differences between foot models than normal children.

2. Methods

2.1. Subjects

Nine normal children (mean 8.1 years old (SD 1.6 years old), mean 135.2 cm (SD 10 cm), mean 30.9 kg (SD 6.5 kg)) and nine flat feet children (mean 8.2 years old (SD 3.4 years old), mean 135 cm (SD 19.4 cm) and mean 34 kg (SD 13 kg) were recruited. Every participant was examined using a homogenous clinical exam, gave informed consent, while the experiment was approved by the local ethical committee. Children from the flat feet group were selected by pediatric orthopedists after a standardized clinical examination. A complete clinical assessment was performed on each participant, in order to collect joint ranges of motion and skeletal torsions. From this examination, clinical knee valgus, knee extension, rearfoot valgus, forefoot abduction and supination were measured (Viehweger et al., 2007). It has been assessed that children had an idiopathic flexible flat foot by ensuring they had a rearfoot valgus value greater than the 4° physiological value and a medial arch flattening when standing (Mosca, 2010). These two specific deformations had to disappear in a non-weight bearing position, in order to exclude non-idiopathic flexible flat feet. Flat feet participants had no neurologic symptom, nor syndromes or synostosis.

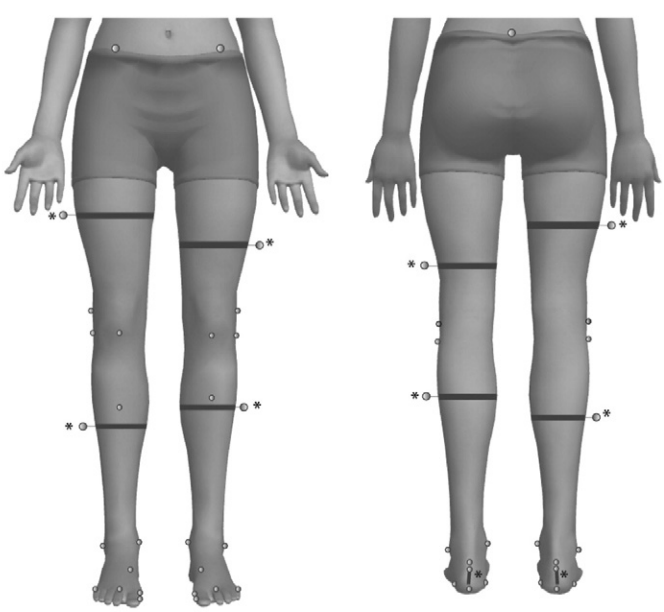

Fig. 1. Markers positioning. Markers positioning used for Plug in Gait and OFM computations including ancillary devices. (a) Rear view of lower limb markers positioning. (b) Front view of markers positioning. Black stars * identify ancillary markers.

2.2. Data collection

Reflecting markers were positioned on foot and lower limbs anatomical landmarks according to the OFM (Stebbins et al., 2006) and Plug in Gait models (Fig. 1). Ancillary devices (markers marked with black stars on Fig. 1) were used to help in reconstructing the orientation of the bony segments (Pasini Neto et al., 2012; Böhm and Döderlein, 2012). Markers representing both models were placed at the same time. First, markers locations were registered in a standing static position in order to perform a static calibration of the kinematic model. Then, a first walking trial was performed in order to check the marker positioning on the subjects. Then, the subjects performed 7 barefoot 5-meter walking trials, at comfortable self-selected walking speed. The children were told to walk naturally and had a training period to get used to the laboratory set-up. Kinematic data were acquired according to a widely used clinical setup using a 6 cameras optoelectronic motion capture system (Vicon, Oxford, UK, 100 Hz data acquisition). Ground reaction forces were synchronously recorded using two embedded AMTI force plates (OR6 series, Advanced Mechanical Technology, Inc., Watertown, USA) sampled at 1000 Hz and placed in the middle of the pathway. One gait cycle was selected for each trial, beginning when the foot hits the force plate. Trials were validated when children hit the first force plate with right foot and the second with left foot. Force plates were used for detecting the heel contact and toe off.

2.3. Foot and ankle modeling

The Oxford Foot Model defines the Tibia coordinate system origin at the center of the ankle joint. The longitudinal axis connects the ankle and knee joint centers (both calculated from ankle and knee markers), the mediolateral axis is orthogonal to the first one and follows the inter-malleolar axis, while the anteroposterior axis is calculated as the direct cross product of the two firsts. The rearfoot coordinate system origin is located at the heel marker. The vertical axis is defined between the heel marker and the marker situated on the Achilles' tendon. The longitudinal axis is orthogonal to the first one, in the plane formed by the three markers of the calcaneum (heel, internal and external calcaneum markers). The third is calculated as a direct cross product of the two firsts. The Euler sequence used for angle computation is flexion/extension, adduction/abduction, and internal/external rotation at last.

The Plug in Gait model defines the origin of the tibia coordinate system at the center of the ankle joint. The vertical axis connects the ankle to the knee joint center. The mediolateral axis is defined with the ankle malleolar marker follows the inter-malleolar axis, and the anteroposterior axis is orthogonal to the two others.

The foot segment is defined using three markers placed at the heel (identical to the OFM), over the second metatarsal head, and at the ankle external malleoli. The center of the foot coordinates system is located at the marker situated at the second metatarsal head. The longitudinal axis of the foot is defined using the heel marker. The mediolateral axis is calculated using the ankle marker and is orthogonal to the longitudinal axis. The vertical axis is mutually directly orthogonal to the two others. The same Euler rotation sequence as the OFM is used for ankle kinematics.

2.4. Data analysis

Raw data were reconstructed using Nexus software (Nexus, Vicon, Oxford, UK). Woltring filter was used to fill missing trajectories where no gaps wider than 5 samples were allowed to be filled. The data were filtered using a zero time lag 4th order low-pass Butterworth (net cut-off frequency: 6 Hz), then time normalized based on events detected with the force plate. For each subject, the normalized trials were averaged over the seven trials to get a single representative cycle per subject. Five clinically relevant points of