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Functional units of the human foot

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Abstract

Functional units in the human foot provide a meaningful basis for subdivisions of the entire foot during gait analysis as well as justified simplifications of foot models. The present study aimed to identify such functional units during walking and slow running. An invasive method based upon reflective marker arrays mounted on intracortical pins was used to register motion of seven foot bones. Six healthy subjects were assessed during walking and four of them during slow running. Angle–angle diagrams of corresponding planar bone rotations were plotted against each other and used to establish functional units. Individual functional units were accepted when the joints rotated temporally in phase and either (i) in the same direction, (ii) in the opposite direction, or (iii) when one of the two joints showed no rotation. A functional unit was generalized if all available angle–angle diagrams showed a consistent pattern.

A medial array from the navicular to the first metatarsal was found to perform as a functional unit with parts rotating in the same direction and larger rotations occurring proximally. A rigid functional unit comprised the navicular and cuboid. No other functional units were identified. It was concluded that the talus, navicular, and medial cuneiform should neither be regarded as one rigid unit nor as one segment during gait analysis. The first and fifth metatarsals should also be considered separately. It was further concluded that a marker setup for gait analysis should consist of the following four segments: calcaneus, navicular–cuboid, medial cuneiform–first metatarsal, fifth metatarsal.

Keywords: Functional units; Foot bone kinematics; Intracortical pins

1. Introduction

The human rear- and midfoot is a complex structure consisting of over 10 major and minor joint articulations between a dozen bones. Most of the foot bones are considerably small and movement capture using three markers per bone is not possible due to spatial limitations. Therefore, simplifications are required. Assuming that only negligible motion takes place within the midfoot, most previous investigations on gait analysis have regarded the midfoot as one segment [1,2]. Along the same line of thinking simplifications are also accepted in modeling. Commonly, several bones are combined to rigid units resulting in models which are easy to handle [3,4].

However, invasive *in vivo* studies have demonstrated considerable motion between midfoot bones during quasi-static foot excursions [5,6], as well as during walking [7] and slow running [8] (e.g. mean dorsi-/plantarflexion between the navicular and the medial cuneiform of about 10°). Furthermore, based on anatomical studies, pioneers of foot research already suggested accompanied rotations in the talo-calcaneal and calcaneo-cuboid joints [9].

Consequently, it is suggested to reconsider the partition of the foot into rigid units. For that purpose the term functional unit is proposed and is defined as follows: a functional unit is present when its bones rotate either (i) in the same direction, (ii) in the opposite direction, or (iii) when one or more bones show no rotation. This paper focuses on

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rotations and not translations, which are negligibly small at the rearfoot joints during physiological movements [10]. In all bones of the proposed functional units the rotation reversal had to take place simultaneously. Therefore, the term functional unit is understood here to describe movements at joints acting together during the entire stance phase. The term is not synonymous with any 'functional characteristics' of the foot, such as shock absorbing characteristics or behavior as a rigid lever.

The present work aims at the identification of functional units in the rear- and midfoot during the stance phase of walking and slow running. The advantage of establishing functional units is to provide a basis for justified simplifications of bone movements in future foot models as well as for marker placement in conventional gait analyses.

2. Methods

The study was conducted on six healthy male volunteers (mean age 38 years (range 28–55 years); mean weight 85 kg (71–110 kg); mean height 181 cm (176–183 cm)). Informed consent was obtained from all subjects in accordance to the ethical committee of Huddinge University Hospital, Sweden.

2.1. Data collection

Prior to the collection of intracortical pin data subjects were acquainted with the laboratory and the 9.5 m track. Subjects performed barefoot walking and running trials to determine their preferred cadence which was then set with a metronome to maintain movement consistency. The surgical insertion of the intracortical pins is described in detail elsewhere [8]. In summary, selfdrilling pins (1.6 mm in diameter) were inserted under local anesthetic into the calcaneus, talus, cuboid, navicular, medial cuneiform, first and fifth metatarsal, and a reflective marker triad was attached to each. Subjects performed as many practice walks as required for them to feel comfortable and to determine their preferred cadence. Kinematic data were collected using a 10 camera opto-electrical system (Qualysis, Göteborg, Sweden) at a sampling rate of 240 Hz. The ground reaction force was measured with a force plate (Kistler, Winterthur, Switzerland) to check consistency between walking and running with and without intracortical pins inserted. It became evident that the pin insertion did not significantly alter the subjects' walking and running pattern [7,8].

Ten walking trials were registered for all six subjects; only four subjects (sub1–sub4) were able to perform 10 slow running trials, due to impingement of the marker triads.

2.2. Kinematic analysis

Non-anatomical coordinate systems directly calculated from the 3D location of the marker arrays of each bone were aligned with the global coordinate system during relaxed standing. Relative to this reference, individual bone movement was determined for each motion analysis frame collected. Rotations at foot joints were then calculated using the helical axis approach [11]. Each attitude vector (product of helical axis rotation and helical axis unit vector) was decomposed along the three axes of the coordinate system of the proximal bone to receive planar joint rotations. Planar rotations of adjacent joints were then used to create angle–angle diagrams, which provided the basis to identify functional units.

In one subject (sub1) the marker triad of the calcaneus rotated at some stage during the running trials. Therefore, all joints involving the calcaneus had to be excluded. In subject 2, one talar marker was partly undetectable during walking. As a consequence, joint rotations involving the talus could not be processed for that subject. Subject 6 had no pin drilled in the talus and therefore no talar motion was available.

2.3. Identification of functional units

The procedure to identify functional units included four steps:

Step 1 Listing of potential functional units. Five functional units were defined, three along the longitudinal axis of the foot and two across it. These consisted of the following bones: talus–navicular–medial cuneiform (proximal medial array), navicular–medial cuneiform–first metatarsal (distal medial array), calcaneus–cuboid–fifth metatarsal (lateral array), navicular–cuboid vs. talus–calcaneus (proximal cross array), and first and fifth metatarsal vs. medial cuneiform and cuboid (distal cross array).

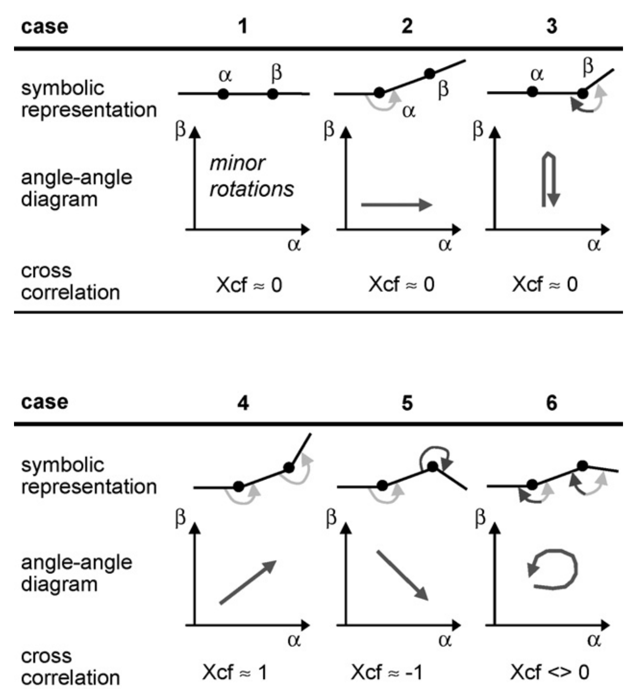

Fig. 1. Six cases of imaginable functional relations between planar rotations of two adjacent joints each with (i) a symbolic representation of two joints given as circles with α-angular and β-angular displacements, (ii) related angle–angle diagrams, and (iii) expected cross-correlation coefficient Xcf. Case 1 shows a rigid unit with no or minor rotations in both joints. Case 2 and 3 characterize motion in only one joint. Case 4 shows α and β rotations in the same direction whereas case 5 show α and β rotations in opposite directions. Case 6 represents a combination of the cases 4 and 5; its pattern indicates a time shift between the two angular displacements.