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Reliability of tarsal bone segmentation and its contribution to MR kinematic analysis methods

P. Wolf [a,*], R. Luechinger [b], A. Stacoff [a], P. Boesiger [b], E. Stuessi [a]

[a] Institute for Biomechanics, ETH Zurich, ETH Hönggerberg HCI E451, Wolfgang-Pauli-Str. 10, 8093 Zurich, Switzerland
[b] Institute for Biomedical Engineering, University and ETH Zurich, Gloriastr. 35, 8092 Zurich, Switzerland

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Abstract

The purpose of this study was to determine the reliability of tarsal bone segmentation based on magnetic resonance (MR) imaging using commercially available software. All tarsal bones of five subjects were segmented five times each by two operators. Volumes and second moments of volume were calculated and used to determine the intra- as well as interoperator reproducibility. The results show that these morphological parameters had excellent interclass correlation coefficients (>0.997) indicating that the presented tarsal bone segmentation is a reliable procedure and that operators are in fact interchangeable.

The consequences on differences in MR kinematic analysis methods of segmentation due to repetition were also determined. It became evident that one analysis method – fitting surface point clouds – was considerable less affected by repeated segmentation (cuboid: up to 0.2°, other tarsal bones up to 0.1°) compared to a method using principal axes (cuboid up to 6.7°, other tarsal bones up to 0.8°). Thus, the former method is recommended for investigations of tarsal bone kinematics by MR imaging.

Keywords: Tarsus; Computer-assisted image processing; Reliability; Methods of MR kinematic analyses

1. Introduction

Currently, magnetic resonance (MR) imaging is increasingly used in the research of foot biomechanics. The process involved in achieving three-dimensional (3D) reconstructions of the bones to a high degree of precision is of importance because at present the reconstructed bony surfaces provide the morphological basis of finite element models of the foot [1–3]. Furthermore, the volumes of foot bones enable construction of a principal axes coordinate system which can be used to analyze foot kinematics with MR imaging [4,5]. In contrast to common stereophotogrammetry, such an approach combined with recently developed MR compatible foot positioning and loading devices provides new insights into tarsal bone kinematics [6–8]. For this purpose MR imaging is superior to any other image based procedures because of its non-invasive character without harmful radiation [5,7].

The 3D reconstruction of the tarsal bones is based on segmented bony parts in the respective MR images. If this image data processing involves operator interaction, precision errors are to be expected [9]. The reliability of open-source reconstruction solutions has frequently been reported in the publication of the method [10–13]. The reliability of common commercial 3D reconstruction software, which is commonly used in clinical and scientific environments, has been primarily investigated in the field of brain tissue volumetry [14–16], but has not been reported for morphological parameters of tarsal bones.

If principal axes or surface point clouds providing MR kinematic analyses are based on semiautomatic segmentation, the accuracy of these analysis methods will be affected by the operator performing the segmentation. In the field of tarsal biomechanics, this has been addressed in studies using an open-source reconstruction solution and principal axes coordinate systems [5,13] but it has not been done so in studies using commercial reconstruction software and surface point clouds.

Thus, the purpose of this study was to evaluate the intra- and interoperator reproducibility of tarsal bone segmentation performed with commercially available software (AMIRA 3.5, Konrad-Zuse Zentrum für Informationstechnik Berlin,

* Corresponding author. Tel.: +41 44 63 36 186; fax: +41 44 63 31 124.
E-mail address: pwolf@ethz.ch (P. Wolf).

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Germany). The following morphological parameters of the calcaneus, cuboid, navicular, and talus and were investigated: volume, moments of volume and the orientation of principal axes coordinate systems. Finally, the influence of repeated segmentations on the accuracy of a MR kinematic analysis method based upon principal axes was determined and compared to an MR kinematic analysis method using surface point clouds.

2. Materials and methods

2.1. Subjects

Five volunteers without signs of musculoskeletal diseases participated in this study (two females, three males). The different foot and shoe sizes (EUR 36, 38, 43, 46, 49) were not only chosen to reflect variation in the size of tarsal bones but also to estimate the precision of the segmentation in general [17]. Informed written consent in accordance to the local research ethics committee was obtained from all subjects.

2.2. Data acquisition

Imaging was performed with a 3 T whole-body MR unit (Intera 3T, Philips Medical Systems, Best, The Netherlands) equipped with a Quasar Dual gradient system (gradient strength up to 80 mT/m and gradient slew rate up to 200 mT/[m ms]). The right lower leg and rearfoot were placed on a 12-element synergy spine coil (Philips Medical Systems) in neutral position and fixed by sandbags. A 3D T1-weighted gradient echo sequence with water selective excitation and second-order shimming was used to obtain fat suppressed, high-contrast and high-resolution images of the tarsal bones. Sequence parameters were as follows: repetition time 16 ms, echo time 4 ms, and flip angle 11°; 200 mm field of view; a 288 × 273 acquisition matrix; Fourier interpolated to 512 × 512 pixels; 1.4 mm thick overcontinuous slices with 50% slice overlapping. Thus, the measured spatial resolution was 0.69 mm × 0.73 mm × 1.4 mm and the resolution of the reconstructed images was 0.39 mm × 0.39 mm × 0.7 mm. For each subject 100 sagittal slices were acquired during 7 min (Fig. 1).

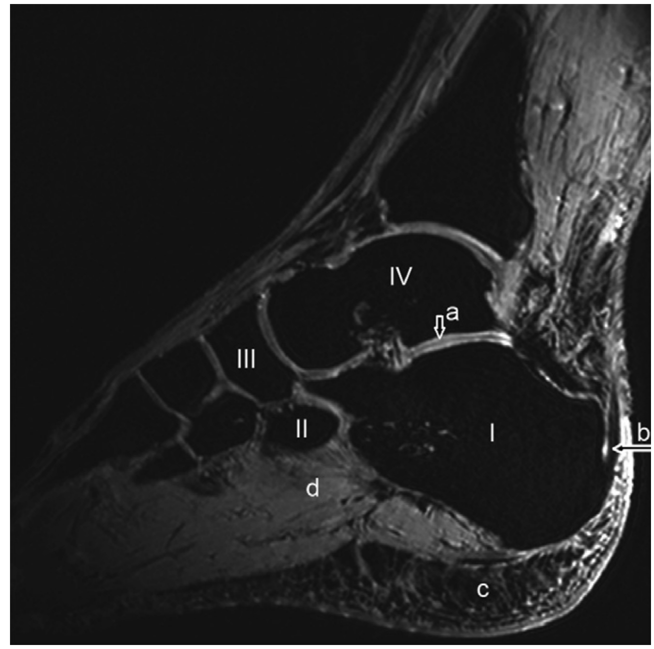

Fig. 1. Sagittal MR image of tarsal bones. Fat supressed 3D T1-weighted gradient echo sequence with selective water excitation. Calcaneus (I), cuboid (II), navicular (III), talus (IV), and cartilage (a), Achilles tendon (b), heel fat pad (c) and musculus quadratus plantae (d).

The signal intensities of tarsal bones, joint cartilage, fatty tissue (at border of heel fat pad), muscle (m. quadratus plantae), Achillis tendon, and background noise were measured for all subjects. Contrast-to-noise ratios (CNR) were calculated as the difference between the mean signal intensities of non-bone tissues (SI_i) and the signal intensity of bone tissue (SI_{bone}) divided by the standard deviation (SD) of noise [$(SI_i - SI_{bone})/SD_{noise}$]. The standard deviation of noise was estimated by the mean signal intensity of air [18]. Contrast-to-noise ratio between bone and cartilage (fatty tissue, muscle, tendon) was found to be 55.0 ± 11.3 (54.6 ± 12.6, 50.7 ± 9.3 and 4.5 ± 4.1). These ratios outline the high-contrast quality of the images.

2.3. Data processing

The 3D reconstruction of the tarsal bones was performed with the AMIRA software. The appropriate image pixels were assigned to the specific tarsal bones using an intensity threshold function. This was first conducted slice by slice in the acquisition plane. Thereafter, the result was controlled by the operator in the other two perpendicular planes. Since vessels and tendons exhibited intensities similar to those of the tarsal bones (see also CNR) the operators' duty was to check whether these non-bony tissues were erroneously segmented and therefore required correction. In this manner, the operators were able to segment a complete tarsal bone in 20–40 min depending on experience and bone size.

The image data stacks of the five subjects were set anonymously, each replicated five times, and set in a random order. This ensured that the segmentation conditions (i.e. threshold) had to be defined by the operators for each data stack individually. On the basis of these 25 image data stacks operator *A* as well as *B* (C as well as D) segmented the calcaneus and cuboid (the navicular and talus). Therefore, each bone was segmented a total of 50 times. Each operator segmented two to three datasets a week. Thus, the overall time to complete the whole segmentation of all image data sets was about 3 months.

2.4. Morphological parameters

Volume and surface area of reconstructed bones were calculated after applying a built-in AMIRA function to smooth by subvoxel-weights. A surface point cloud of each bone was then imported into MatLab 6.5 (MathWorks, Massachusetts). Cubes with the density set arbitrarily to 1 g/cm^3 and side length to 0.7 mm were positioned in the surface point cloud. Second moments of volume and related principal axes were subsequently calculated (Fig. 2) whereby cubes on the surface were weighted by a factor of 0.5.