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Does a specific MR imaging protocol with a supine-lying subject replicate tarsal kinematics seen during upright standing?[a]

Bildet ein spezifisches MR-Verfahren mit rücklings liegendem Probanden die tarsale Kinematik unter stehenden Bedingungen nach?

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Abstract

Magnetic resonance (MR) imaging is becoming increasingly important in the study of foot biomechanics. Specific devices have been constructed to load and position the foot while the subject is lying supine in the scanner. The present study examines the efficacy of such a newly developed device in replicating tarsal kinematics seen during the more commonly studied standing loading conditions. The results showed that although knee flexion and the externally applied load were carefully controlled, subtalar and talo-navicular joint rotations while lying during MR imaging and when standing (measured opto-electrically with markers attached to intracortical pins) did not match, nor were they systematically shifted. Thus, the proposed MR protocol cannot replicate tarsal kinematics seen during upright standing. It is concluded that specific foot loading conditions have to be considered when tarsal kinematics are evaluated. Improved replication of tarsal kinematics in different postures should comprehensively consider muscle activity, a fixed hip position, and a well-defined point of load application.

Keywords: intracortical pins; magnetic resonance imaging; subtalar joint kinematics; talo-navicular joint kinematics; tarsal bones.

Zusammenfassung

Die Magnetresonanz- (MR) Tomographie gewinnt in der Fußbiomechanik immer mehr an Bedeutung. Um den Fuß positionieren und belasten zu können, während der Proband rücklings im Tomographen liegt, wurden spezifische Aufbauten konstruiert. Die vorliegende Studie prüft die Effektivität eines derartigen, neu entwickelten Aufbaus hinsichtlich der Imitation der tarsalen Kinematik, die sich unter den üblicherweise untersuchten stehenden Bedingungen ergibt. Die Ergebnisse zeigten, dass trotz sorgfältiger Kontrolle der Knieflexion und der äußeren Last die Rotationen des unteren Sprunggelenks sowie talo-navikularen Gelenks während dem Liegen im MR-Tomographen nicht mit denen während des Stehens (optoelektrisch gemessen anhand von im Knochen fixierten Drähten) übereinstimmen, wobei die Ergebnisse auch nicht systematisch verschoben sind. Das vorgeschlagene MR-Verfahren ist daher nicht in der Lage, die tarsale Kinematik während des Stehens abzubilden. Folglich sind bei Betrachtungen der tarsalen Kinematik die spezifischen Belastungen des Fußes zu bedenken. Eine verbesserte Imitation der tarsalen Kinematik in verschiedenen Körperhaltungen sollte sorgfältig die Aktivität der Muskulatur, eine fixierte Hüfte sowie einen exakt definierten Kraftangriffspunkt berücksichtigen.

Schlüsselwörter: Kinematik des talo-navikularen Gelenks; Kinematik des unteren Sprunggelenks; Knochenschrauben; Magnetresonanztomographie; tarsale Knochen.

Introduction

In the past, kinematics of the tarsal bones (calcaneus, cuboid, navicular and talus) have been examined by either two- and three-dimensional X-ray stereophotogrammetry [3, 8–10, 23] or by opto-electrical registration of markers on intracortical pins [1, 13, 14, 18–20]. However, these methods are invasive or ionising and cannot be used routinely in living subjects. The alternative approach, using skin mounted markers, is also problematic because the talus is inaccessible, and the cuboid and navicular are too small to mount the three required markers. Furthermore, motion of the bones relative to the skin limits the validity of kinematic data derived from skin-mounted markers [11, 22, 24].

Magnetic resonance (MR) imaging overcomes these methodological limitations, provides equally accurate motion data [25], and is becoming increasingly popular for investigation of tarsal kinematics [12, 15, 17, 21]. However, MR imaging requires that the subject is supine, whereas it is desirable to study the foot under conditions

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[a] The first author received a conference award for his poster entitled *Transmission within the tarsal gearbox* at the Combined Annual Meeting of DGBMT, ÖGBMT and SGBT (Zurich, Switzerland, 2006). The methods section of this poster was based on the non-invasive approach presented in this paper.

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of standing or walking. In this context, an MR imaging procedure was developed to enable spatial foot positions and loading to be controlled whilst supine in the MR scanner [26]. The MR imaging protocol involves loading the plantar surface of the foot using a horizontal loading device while the subject is supine in the MR scanner. This allows investigation of tarsal kinematics under near-bodyweight loading conditions while the foot is pronated and supinated using wedged platforms. The open question is whether or not this MR imaging protocol adequately matches a standing foot loading condition. Thus, the aim of this study was to evaluate the new MR protocol by comparing tarsal kinematics during foot pronation and supination measured using (1) the MR imaging protocol and (2) intracortical pins during standing. The hypothesis was that the tarsal kinematics from the MR protocol would match those measured during standing.

Materials and methods

Subjects

The study was conducted on three male volunteers without signs of musculoskeletal diseases aged 28, 33, and 55 years, 175, 180, and 182 cm high, and weighing 71, 75, and 80 kg, respectively. Informed written consent in accordance with the guidelines of the local research Ethics Committee was obtained from all subjects.

MR procedure

Subjects lay on the MR table and their right foot was fixed into the foot-loading and -positioning device [25, 26]. A load of 0.5 × body weight was applied to the board under the right foot, simulating relaxed standing. Three different wooden blocks were placed under the foot to control foot position: a flat block (neutral), a 15° wedged “pronating” block (10.8° eversion, 3.3° dorsiflexion, 9.8° abduction), and a 15° wedged “supinating” block (10.8° inversion, 3.3° plantarflexion, 9.8° adduction), as shown in Figure 1A. The subject’s foot was aligned on the blocks according to the longitudinal axis of the foot defined by the second toe and the most posterior aspect of the heel. The extent of the pronation and the ratio of frontal to transverse to sagittal plane rotation was based on: (i) the commonly reported 10° of calcaneal eversion during the initial stance phase of running [6, 19]; and (ii) on an approximated subtalar axis with an orientation of 41° relative to the transverse plane and 17° to the sagittal plane [7, 16].

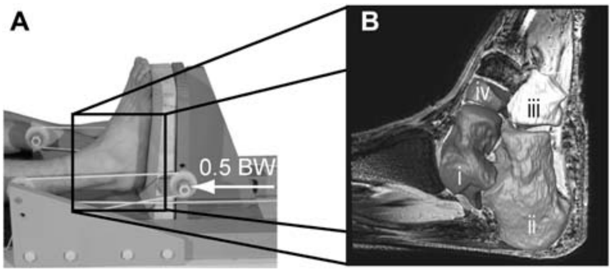

Figure 1 (A) Foot positioning and loading device of the MR imaging procedure. A load of half bodyweight was applied axially under the heel. (B) MR image with 3D reconstructed tarsal bones: (i) talus, (ii) calcaneus, (iii) cuboid, and (iv) navicular.

Imaging was performed on a 3-T whole-body MR unit (Intera 3T, Philips Medical Systems, Eindhoven, The Netherlands) with two synergy coil elements (Sense Flex M, Philips Medical Systems). A 3D T1-weighted gradient echo sequence with the following parameters was used: repetition time, 16 ms; echo time, 4 ms; flip angle, 11°; field of view, 200 mm; acquisition matrix, 288×273; Fourier interpolation, 512×512 pixels; and 1.4-mm-thick over-continuous slices with 50% slice overlapping. Thus, the resolution of the reconstructed images was 0.39×0.39×0.7 mm^3 (Figure 1B). For each subject and test condition, 130 sagittal slices were acquired during approximately 9 min.

3D reconstruction of the tarsal bones (Figure 1B) was performed semi-automatically by one operator using AMIRA software (v.3.5, Konrad-Zuse Zentrum für Informationstechnik Berlin, Germany). The resulting surface points were imported into MatLab (v.7.0, MathWorks, Natick, MA, USA). An iterative closest-point algorithm [4] was used to register the surface point cloud of each bone obtained in the neutral position with those during pronation and supination. This algorithm can be summarised as follows. First, the matching points of a reference position (in the present study, the neutral foot position) and of a final position (in the present study, the two foot excursions) are computed based on the minimum distance. Second, the corresponding points are registered by a least-square singular value decomposition. Third, the resulting transformation is applied to the reference point cloud. This iteration is terminated when the change in mean square error of the distances between the reference point cloud and the point cloud of the final position falls below a defined threshold [4].

The overall coordinate transformations were then used to calculate tarsal joint motion expressed as finite helical axis rotations. These were projected onto the axes of the reference bone under consideration of the helical axis orientation [27]. The overall error introduced by this MR data processing was less than 0.05°, whereas the difference for repeated joint rotations was less than 3° [26].

Opto-electrical registration

Intracortical pins (1.6 mm in diameter) were inserted under local anaesthetic into the calcaneus, cuboid, navicular, and talus, and a reflective marker triad was attached to each (Figure 2). (Pins were inserted into other bones for other studies; one of them describing the procedure in more detail has recently been published [2].) Kinematic and kinetic data were collected using a ten-camera opto-electrical system (Qualysis, Göteborg, Sweden) at 240 Hz and a force plate (Kistler, Wintherthur, Switzerland). Analysis of stance times and ground reaction forces with and without these pins in place revealed that gait was not remarkably modified by the presence of the pins. Coefficients of multiple correlation for tibial motion and ground reaction forces were moderate to high, and the duration of stance phases was not significantly slower during running with pins compared to running without pins [2]. Thus, it was assumed that insertion

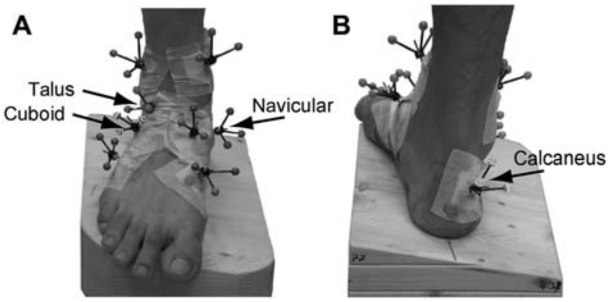

Figure 2 (A) Anterior view of standing on the pronation block. The marker triads of the intracortical pins of the talus, cuboid, and navicular are emphasised. (B) Posterior view of standing on the supination block. The calcaneal marker triad is highlighted.

of the pins did not significantly affect the kinematics, particularly not during the standing positions used in the present study.

Technical coordinate frames (a non-anatomical coordinate system directly calculable from the 3D location of the marker arrays) for each bone were determined in the global coordinate system. The neutral standing trial was matched to the conditions in the MR imaging by reproducing the neutral foot block position. Individual bone motion relative to the neutral bone location was determined for the pronation and supination foot positions. The contralateral foot stood on the neutral block, allowing straight leg standing and a neutral pelvis position. Each foot excursion was repeated five times. The subjects descended from the blocks between the trials.

Applying the same method as used in the MR protocol, joint rotations were computed using the helical axis approach [27]. The analysis focused on the subtalar and talo-navicular joints, since the rotations between other tarsal bones were found to be small during the foot excursions described (calcaneus-cuboid, 2–6°, navicular-cuboid, <2° [25]).

Results

Rotations of the calcaneus relative to the talus in response to quasi-static foot pronation and supination are presented in Figure 3. Rotations determined with the MR procedure (circles) were only occasionally within the inter-quartile range of the five standing trials measured with intracortical pins, and no systematic shift was present. Similar results were found for the talo-navicular joint. No subject showed consistently comparable rotations when lying supine and when standing upright (Figure 4).

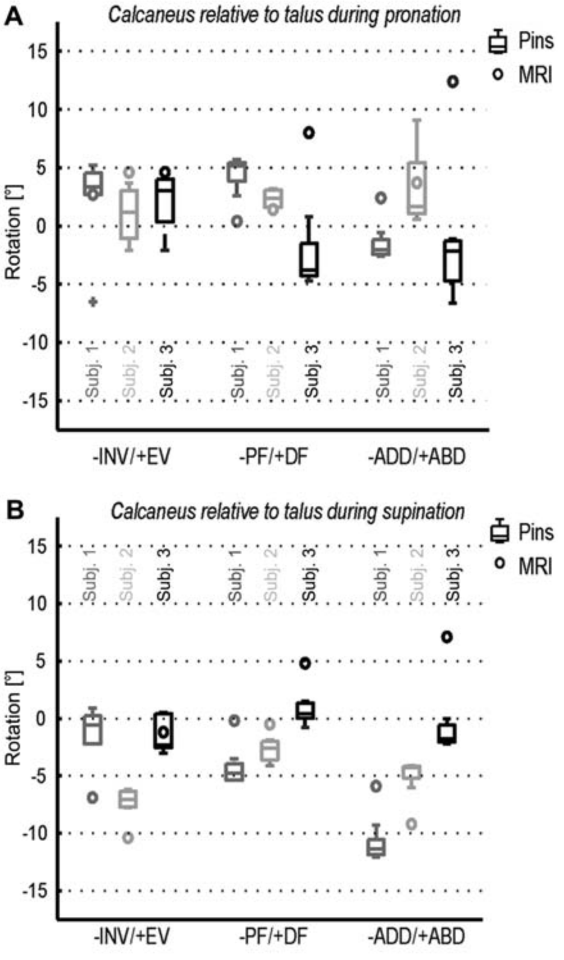

Figure 3 Subtalar joint rotations in response to quasi-static foot (A) pronation and (B) supination.
Results of repeated measurements of the inserted intracortical pins are shown as boxplots, and results of MR imaging as circles. Lying supine (during MR imaging) and standing upright (with intracortical pins) resulted in different rotations, since the results of the MR imaging procedure were not consistently within the lower and upper quartile of the intracortical pin measurements.

Discussion and conclusion

This study examined the feasibility of using an MR loading device to replicate the quasi-static tarsal kinematics seen in upright posture.

The results showed that tarsal joint rotations while lying supine in the MR scanner did not systematically match with corresponding rotations during standing (Figures 3 and 4). Differences between the median standing (opto-electrical measurement) and the lying supine (MR imaging) results were of up to 10° in magnitude, which is at least twice the measurement error of both methods. Thus, although knee flexion and the externally applied load were carefully controlled during lying and standing, the motion of the tarsal joints in the MR protocol did not imitate those in an upright posture.

There is a range of reasons why the tarsal kinematics differ. Clearly, we would expect some degree of difference between how the tarsal bones move during the two experiments simply because they were carried out on different days [5]. Also, subtle changes in hip position, in combination with slightly altered points of load application (particularly during the measurements with inserted intracortical pins), would contribute to the different tarsal joint rotations. Furthermore, in contrast to standing upright, lying supine does not require activity of the following muscles inserting at the midfoot: tibialis anterior, tibialis posterior, peroneus brevis, and peroneus longus. Activity in these muscles may have resulted in tarsal bone rotations and thus may have also contributed to the differences observed.

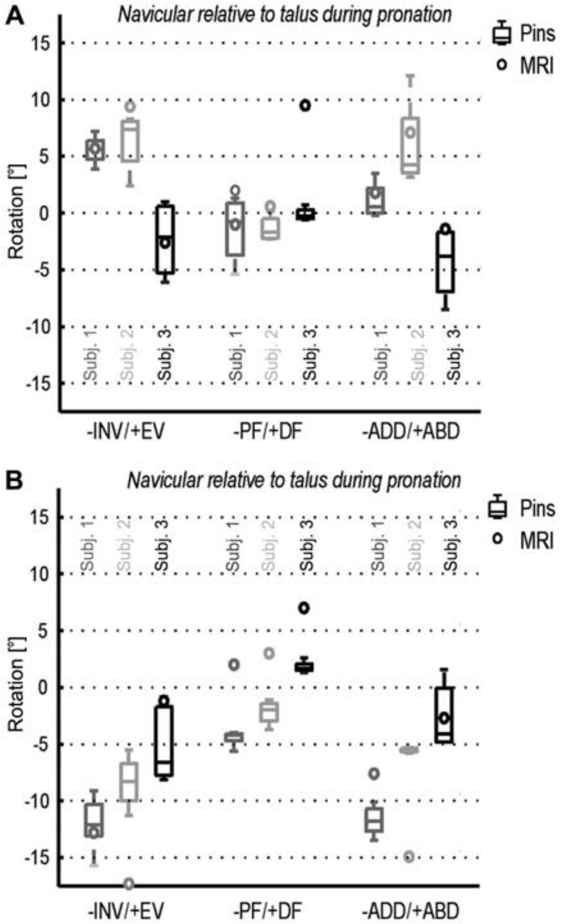

Figure 4 Talo-navicular rotations in response to quasi-static foot (A) pronation and (B) supination.
Results of repeated measurements of the intracortical pin marker triads are shown as boxplots, and results of MR imaging as circles. Similar to the subtalar joint, lying supine during MR imaging and standing upright with intracortical pins resulted in different rotations.

In conclusion, despite using a specific foot loading device, the proposed MR protocol cannot replicate tarsal kinematics seen during upright standing. Tarsal kinematics are influenced by many factors; consequently, improved replication of tarsal kinematics in different postures would require (i) additional consideration of muscle activity; (ii) external foot positioning and loading; and (iii) greater constraints on the hip position and point of load application. In general, specific foot loading conditions have to be considered when tarsal kinematics are measured and compared.

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