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Bone shape difference between control and osteochondral defect groups of the ankle joint

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SUMMARY

Objective: The etiology of osteochondral defects (OCDs), for which the ankle (talocrural) joint is one of the common sites, is not yet fully understood. In this study, we hypothesized that bone shape plays a role in development of OCDs. Therefore, we quantitatively compared the morphology of the talus and the distal tibia between an OCD group and a control group.

Methods: The shape variations of the talus and distal tibia were described separately by constructing two statistical shape models (SSMs) based on the segmentation of the bones from ankle computed tomography (CT) scans obtained from control (i.e., 35 CT scans) and OCD (i.e., 37 CT scans) groups. The first five modes of shape variation for the SSM corresponding to each bone were statistically compared between control and OCD groups using an analysis of variance (ANOVA) corrected with the Bonferroni for multiple comparisons.

Results: The first five modes of variation in the SSMs respectively represented 49% and 40% of the total variance of talus and tibia. Less than 5% of the variance per mode was described by the higher modes. Mode 5 of the talus ($P = 0.004$) primarily describing changes in the vertical neck angle and Mode 1 of the tibia ($P < 0.0001$) representing variations at the medial malleolus, showed statistically significant difference between the control and OCD groups.

Conclusion: Shape differences exist between control and OCD groups. This indicates that a geometry modulated biomechanical behavior of the talocrural joint may be a risk factor for OCD.

Introduction

The ankle (talocrural) joint is the second most common site for osteochondral defects (OCDs), exceeded in frequency only by the knee[1]. The true incidence of OCDs in general population is currently unknown[2]. In a study following US military personnel during a 10 years period (1999–2008), the average incidence of OCDs of the talus has been stated to be 27 per 100,000 people[2]. In another study, it has been reported that 15–25% of ankle injuries, from which approximately 1 in 10,000 persons per day suffer, result in OCDs[3]. In the ankle, tibia OCDs have been stated to be rare as compared to the incidence of talus OCDs. In a study consisting of 428 ankles with OCDs, the medial talar dome lesions (i.e., 269 OCDs, 62%) have been found to be more common in comparison to lateral (i.e., 143 OCDs, 34%) and central (i.e., 16 OCDs, 4%) talar dome lesions[4].

OCDs can lead to chronic ankle joint pain, decreased level of patient activity, and osteoarthritis (OA)[2]. To take preventive measures, it is essential to know risk factors that induce OCDs in the talocrural joint. Although OCDs of the ankle joint are extensively studied, its etiology is not yet fully understood[5]. Several

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factors including "local avascular necrosis, systemic vasculopathies, acute trauma, chronic microtrauma, endocrine or metabolic factors"[3], articular incongruency[4], malalignment of the lower limb[4] and genetic predisposition[4] have been proposed to contribute to the risk of developing an OCD. Trauma has been extensively stated to be the main cause of ankle OCDs[6]. 93–98% of lateral and 61–70% of medial dome lesions were found to be related to trauma[6]. The lateral lesions are thought to be caused by a shear mechanism, while medial lesions are results of torsional impaction and axial loading of the talocrural joint[5]. Up to now, no study has investigated possible relation between bone shape and OCD risk in the ankle.

There is a growing evidence[7–9] suggesting that a slight difference in joint mechanics driven by variability in joint morphology may be a risk factor for development and progression of joint diseases. Variations in the acetabular cup of the hip joint (i.e., acetabular dysplasia)[8], the femoral head–neck junction (i.e., cam type impingement), and the acetabular depth (i.e., pincer type impingement) have been found to be associated with OA[8]. Moreover, significantly different shapes of the distal femur and the proximal tibia have been observed between subjects with and without anterior cruciate ligament injuries[7].

Taking all findings into account, it seems plausible that relatively subtle differences in ankle morphology may be associated with the risk of sustaining an OCD. In this study, we hypothesize that the morphologies of the talus and the distal tibia are different between subjects without an OCD and patients with an OCD. Therefore, we aimed to describe the complex geometries of the ankle bones together with shape variances within a population using statistical shape modelling (SSM) technique[10,11] and to quantitatively compare the morphology of the talus and the distal tibia between an OCD group and a control group.

Materials and methods

Two three-dimensional (3D) SSMs were built by segmenting bones from computed tomography (CT) images of the mixed data of subjects without an OCD and patients with an OCD, each corresponding to either talus or distal tibia. Using those SSMs, bone shapes of control and OCD groups were quantitatively compared (Fig. 1).

Image acquisition

Seventy two anonymized CT scans (i.e., 35 CT scans for the control group: 17 female and 18 male, age = 28 ± 5.8 years; and 37 CT scans for the OCD group: 14 female and 23 male, age = 37 ± 12.1 years; there exists a significant difference between the mean ages of two groups based on unpaired *t*-test, $P = 0.0006$), of both left and right ankles, were collected from the Academic Medical Center (AMC, Amsterdam, The Netherlands) and Utrecht Medical Center (UMC, Utrecht, The Netherlands). Control and OCD groups CT scans were checked by experienced radiologists to confirm absence or presence of OCDs in the talocrural joint, respectively. In 5 of 37 OCD group CT scans, bilateral lesions were present in the talocrural joint. Lateral, medial, and central talar dome OCDs were observed in 11, 29, and 2 CT scans of OCD group, respectively.

CT images collected from the AMC were acquired using Philips MX-8000 multidetector CT scanner (Philips Medical Systems, Best, The Netherlands). The acquisition parameters were: effective dose 150 mAs/slice, rotation time 0.75 s per 360°, pitch 0.875, slice thickness 0.6 mm, and ultra-high resolution mode. Tomographic reconstructions were made with a field of view of 154 mm, a slice increment of 0.3 mm, and a matrix of 512 × 512 pixels. The voxel sizes were approximately 0.3 mm × 0.3 mm × 0.3 mm. CT images collected from the UMC were acquired using a 40 detector row CT scanner (LSO PET 40-slice CT scanner, Siemens Healthcare, Erlangen, Germany). The acquisition parameters were: collimation 40 × 0.6 mm, tube voltage 120 kVp, effective dose 40 mAs, rotation time 0.5 s, pitch 0.8, slice thickness 1.5 mm, care DOSE4D, and Care kV dose modulation. Tomographic reconstructions were made with a field of view of 500 mm, and a matrix of 512 × 512 pixels. The B60f sharp reconstruction filter was used. The voxel sizes were approximately 1.0 mm × 1.0 mm × 0.75 mm.

Segmentation

To build the SSMs, the unilateral talocrural joint was segmented from each CT scan. A second user re-segmented three of the joints to evaluate inter-observer variability and its effect on reproducibility of the method used in generation of SSMs. For the OCD group, the contralateral unaffected talocrural joint was segmented assuming bilateral symmetry of the ankle bones[12,13]. In the cases with bilateral lesions (i.e., in five subjects), the talocrural joint that had been less affected by the lesions was selected. The main reason behind these selections was to minimize any inaccuracies that might arise in estimation of the complete shape of the bones, if some part of the bone surface was missing due to lesions.

The bones were segmented using Mimics (version 14.01, Materialise, Leuven, Belgium). During the reconstruction of the 3D bone models, a smoothing factor (i.e., 0.5 with a smoothing iteration of 1) was applied. Smoothing effects for each bone were visually checked to ensure proper definition of the contour of the bones. Using the same software, triangulated bone surfaces were extracted from the segmentation results. As the dataset used in this study was a mixture of left and right side ankles, left side ankles were mirrored in the sagittal plane.

Transection of tibia

The entire volume of the tibia was not visible on all CT scans, necessitating transection of this bone in the axial plane. For each tibia, its subchondral bone surface was automatically determined using a custom-made code developed in Matlab (Matlab R2013b, The Mathworks, Inc., Natick, MA) (Supplementary material) (Fig. 2). The vertices of the triangles located on the subchondral bone surfaces were extracted (Fig. 2). As variations due to differently oriented coordinate systems of CT scans might be seen during transection of the bones and might contribute to bone shape variations, each tibia was scaled and aligned with respect to its subchondral bone surface before transection (Fig. 2). For alignment and scaling, an unbiased registration algorithm was used[14]. Aligned and scaled bones were transected at a level that was defined by the bone for which the smallest volume was visible on the CT-scans (Fig. 2). Transected tibia surfaces were closed by automatic addition of points (Fig. 2) (Supplementary material). Subsequently, they were triangulated using a custom-made Matlab code developed based on the Crust algorithm[15] (Fig. 2).

Registration

Position, orientation, and size differences among all bones of the same type were minimized by aligning and scaling them using an unbiased registration[14] (Supplementary material). This ensures that the remaining differences could be attributed to shape variations only. During the registration process, each bone was represented with 2000 points, which were randomly chosen from the entire set of surface points in a way that sub-selected points were uniformly distributed over the bone surface. The total number of points used to describe each bone shape during the registration