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What is This?
Subtalar Joint Configuration on Weightbearing CT Scan

Fabrice Colin, MD, Tamara Horn Lang, PhD, Lukas Zwicky, MSc, Beat Hintermann, MD, and Markus Knupp, MD

Abstract

Background: Standard values that describe the morphology of the subtalar (ST) joint have previously been obtained from cadaveric studies or by using conventional unloaded radiographs. It is known that these parameters differ significantly from those measured in vivo and in loaded images, limiting the diagnostic value of the previously published morphological parameters in the literature. However, the morphology of the ST joint clearly affects its function. The objective of this study was to determine the morphology of the posterior facet of the ST joint using loaded computed tomography (CT) images and to describe the different configurations found in asymptomatic patients.

Methods: A weightbearing CT scan was performed on 59 patients without any history of hindfoot and ankle pathology. The shape of the posterior facet and the subtalar vertical angle (SVA) were measured in 3 different coronal planes of the ST joint.

Results: The posterior facet was concave in 88% and flat in 12%. The posterior facet was oriented in valgus in 90% and varus in 10% when measured in the middle coronal plane. However, the SVA changed depending on which coronal plane it was measured in.

Conclusion: We believe it is important to get a better insight into the morphological parameters of the ST joint.

Clinical Relevance: Knowledge of subtalar joint morphology could help clarify why certain failures have occurred in reconstructive hindfoot surgery and thus might help plan the surgical procedure to reduce these failures in the future.

Keywords: weightbearing CT scan, subtalar joint, morphology

Introduction

While the ankle joint has been examined and described in numerous morphological and biomechanical studies, only little is known about the subtalar (ST) joint. However, it is well accepted that the ST joint consists of 3 articulating facets: anterior, intermediate anterior, and posterior. The posterior talar articular surface is strongly concave in the sagittal plane and usually flat or minimally concave in the coronal plane. However, in cadaveric and radiological studies, large variations of the ST joint morphology have been described.

Inman described the ST joint as a torque transmitter, in which rotation of the leg is converted into pronation and supination of the foot and vice-versa. The orientation and shape of the ST joint therefore has an important impact on the biomechanical properties of the hindfoot. However, to the best of our knowledge, the radiological anatomy and shape of the ST joint has not been examined and analyzed in detail in an asymptomatic cohort, without any hindfoot pathology.

Plain weightbearing radiographs play an important role in the diagnosis and assessment of hindfoot pathologies. However, newer imaging modalities such as computed tomography (CT) allow more detailed imaging of the intertarsal relationship and are even considered superior in evaluating various bone pathologies. Several groups have developed devices that simulate weightbearing during CT scan examination in a seated position. These studies generally showed that weightbearing had a significant effect on the anatomical changes of the foot configuration in both asymptomatic and pathological foot conditions. However, none of these studies analyzed the morphology of the ST joint. Furthermore, these seated weightbearing CT scan examinations were done using an imaging modality not designed to collect weightbearing images, but nevertheless showed the importance of using weightbearing devices. Nowadays, weightbearing CT scan modalities that allow...
true weight-bearing images are available, and images taken represent the physiological hindfoot morphology found in an upright weight-bearing position.

The shape of the subtalar joint is of importance since the morphology of a joint has an effect on the joint function. Knowing the morphology of the ST joint in asymptomatic patients may serve as a tool to understand the evolution of hindfoot deformity and/or degenerative wear of the ankle and subtalar joint. The hypothesis of this study was that the posterior facet of the ST joint adopted different shapes and orientation on the coronal plane on weightbearing CT in an asymptomatic cohort.

**Methods**

**Population**

This study was conducted in accordance with the Declaration of Helsinki and Guidelines for Good Clinical Practice. The protocol was approved by the Ethics Committee. A total of 59 healthy volunteers informed about the radiation exposure (male, 34; female, 25; mean age, 45 years; range, 18-74) without hindfoot and ankle pathologies after clinical evaluation were included in this study. Patients with previous history of hindfoot and ankle trauma and/or surgery were excluded from this study.

**Radiographic Technique**

CT images were collected starting from 10 cm proximal to the tibiotalar joint to the sole of the foot with the subjects standing upright and fully weightbearing using a cone beam CT (Planmed Verity, Planmed Oy, Helsinki, Finland; 0.2 mm slice thickness, 1 mm slice interval). The CT scan had an anode voltage of up to 96 kV, 7.5 mA, 40 mAs, FOV 13 × 16 cm, and according to a previous study, the maximal estimated radiation dose, using the default adult exposure parameters, was 12.6 μSv. Images were saved as Digital Imaging and Communications in Medicine (DICOM) files, and 3D Multi-Planar Reconstruction (3D-MPR) was performed using an image processing software (OsiriX MD, Pixmeo, Geneva, Switzerland).

**Measurement Methods**

To define the 3 different coronal planes used, the length of the ST joint was measured on a sagittal plane that included the projection of a line connecting the center of the heel and the head of the second metatarsal. A cut through the middle of the ST joint on the sagittal plane was defined as the middle coronal plane used to measure the subtalar vertical angle (SVA). The third anterior coronal plane was defined as 5 mm anterior to the middle coronal plane and the third posterior coronal plane as 5 mm posterior to the middle coronal plane (Figure 1).

The shape of the posterior talar articular surface was determined as being concave or flat on the coronal plane (Figures 2, 3). The articular surface was considered flat if the radius of a circle whose curvature was adjusted/adapted to the articular surface was more than 60 mm.

The orientation of the ST joint was measured using the SVA. Van Bergeyk et al defined the SVA as being the inclination between a line drawn connecting the medial and lateral border of the posterior facet of the ST joint and a vertical line on the coronal plane that is perpendicular to the floor. Values less than 90 degrees were defined as varus and more than 90 degrees as a valgus configuration (Figure 2). To assess the screw-shaped surface of the ST joint, the SVA was measured in 3 different coronal planes (anterior, middle, and posterior planes).

All of the measurements taken were done by a trained orthopaedic surgeon (FC).

**Statistical Methods**

Normal distribution of the data was checked using a Kolmogorov-Smirnov test. A Student t test was used to compare 2 groups. To compare more than 2 groups, a 1-way ANOVA followed by a Bonferroni’s post hoc comparisons test was performed. The degree of correlation was described using the Pearson correlation coefficient. The level of significance was defined as \( P < .05 \). All statistical data analysis was performed using SPSS 21.0 (IBM SSPS, Armonk, New York, USA).

**Results**

The shape of the articular surface of the ST joint was considered on each coronal cut. The geometry of the articular
surface did not change depending on the coronal plane analyzed and was found to be concave in 52 patients (88%) and flat in 7 patients (12%). The SVA of the posterior facet varied according to the coronal plane it measured: anterior, middle, or posterior. Forty-two patients (71%) presented a varus-valgus-valgus configuration (SVA anterior in varus, SVA middle, and SVA posterior in valgus) (Figure 4). Eleven patients (19%) presented a valgus-valgus-valgus configuration. Six patients (10%) presented a varus-varus-valgus configuration. The SVA measured in the middle coronal plane of the posterior facet was in valgus in 53 patients (90%) and in varus in 6 patients (10%). The range of the SVA varied from 67.7 degrees measured in the anterior coronal plane to 122.7 degrees measured in the posterior coronal plane. The SVA measured in the anterior and posterior planes highly correlated with the SVA measured in the middle plane (r = 0.85 and r = 0.82, respectively; P < .001) (Figure 5).

The SVA measured in the middle coronal plane was significantly higher in patients with a flat posterior facet (flat: 103.9 degrees, SD = 4.4 degrees; concave: 97.4 degrees, SD = 6.2; P = .01) (Figure 6).

**Figure 2.** A coronal image taken of a hindfoot using a weightbearing CT scan device. Illustrated is the subtalar vertical angle (SVA), defined as the inclination of the line connecting the medial and lateral aspects of the talus with a vertical line, which is perpendicular to the ground. In this individual, on middle coronal cut of the subtalar (ST) joint, the shape was concave and the SVA was oriented in valgus.

**Figure 3.** An example of an individual with a flat shaped facet on the middle coronal cut of the subtalar (ST) joint of a weightbearing CT scan.

**Discussion**

In this study, weightbearing CT scans were used in patients with asymptomatic clinical morphology of the hindfoot to assess the ST joint configuration in the coronal plane. We found that the ST joint is either shaped concave or flat with an SVA angle ranging from a varus to a valgus orientation when measured in the coronal plane. The majority of the volunteers who participated had a concave shaped ST joint, which was valgus oriented when looking at the posterior facet joint line. The novelty of this study lies in the patient cohort used and the method applied to describe the morphology of the ST joint: (1) asymptomatic volunteers were used and (2) weightbearing CT scans were used. To our knowledge this has not been done previously.

 Earlier anatomical studies have shown that the posterior facet is concave like a ball and socket. In 1941 Manter and later others described the ST joint in cadavers and found that the posterior facet was an oblique, screw-shaped surface in the coronal plane. Subsequent radiological studies showed that the posterior facet was concave, flat, or
slanted on the coronal plane.\textsuperscript{6,13,14} Farsetti et al\textsuperscript{6} were the first to use CT scans to assess the shape of the ST joint on the coronal plane. However, this study was conducted in patients with clubfeet. Of the 108 clubfeet examined, only 12 (11\%) showed a concave shape of the ST joint.\textsuperscript{6}

In contrast, in the present study, we found that in an asymptomatic cohort the shape of the ST joint surface was

\textbf{Figure 4.} This is an example of a varus-valgus-valgus subtalar (ST) joint configuration found on the 3 coronal planes measured using a weightbearing CT scan. The subtalar vertical angle (SVA) anterior, middle, and posterior was oriented in (a) varus, (b) valgus, (c) valgus.

\textbf{Figure 5.} Line diagram of the subtalar vertical angle (SVA) related to its position. The SVA increases in valgus when the measurement was performed posteriorly.

\textbf{Figure 6.} Subtalar vertical angle (SVA) on the middle coronal plane related to the shape of the subtalar (ST) joint. The SVA on the middle coronal plane of the ST joint in the flat shape group was significantly higher in valgus (flat: 103.9 degrees, SD = 4.4 degrees; concave: 97.4 degrees, SD = 6.2; \(P = .01\)).
concave in 88% of the ST joints measured. Only 12% of the patients measured showed a flat ST joint shape. Interestingly, these patients who had a flat ST joint additionally had a more pronounced valgus configuration than the patients with a concave ST joint shape. Thus, we believe that patients with a flat ST joint shape have a limited capacity to compensate for hindfoot deformities, particularly those with a flatfoot or an ankle valgus deformity. In contrast, in patients with a concave shaped ST joint, the joint itself may be able to compensate coronal plane deformities. This is supported by data from anatomical and functional studies.  

Recently, Hayashi et al 10 described the complex interaction of the ankle and the ST joint in malaligned feet in the coronal plane. They suggested that the ST joint is able to compensate for varus in the distal tibia with a progressive valgus inclination. These data further suggest that patients with a concave shaped ST joint thus may more likely benefit from conservative treatment options such as ankle/foot orthosis or insoles than patients with a flat shaped ST joint. However, further studies are necessary to elucidate this.

A further parameter used to describe the ST joint was the SVA. Van Bergeyk et al 26 were the first to describe the SVA in order to assess the hindfoot alignment in chronic lateral ankle instability. Inter- and intraobserver reliability were measured and documented. They reported that the ST joint in the control group (no hindfoot pathophysiology) was oriented in valgus in a majority of the patients examined. Similar to Van Bergeyk et al, our study showed that the orientation of the ST joint, in a majority of the cases, was in valgus (measured in the middle coronal plane: in valgus in 90% and in varus in 10%). However, in contrast to our study, they did not take into consideration that the SVA is dependent on the coronal plane in which it is measured (anterior, middle, or posterior). For example, when measured in the anterior plane, the SVA in a majority of the patients (48 patients, 81%) was in varus. Our data therefore show that depending on the coronal plane in which the SVA was measured, the amount of varus/valgus inclination varied markedly.

It is known that the osseous ankle joint configuration could be a risk factor to develop chronic ankle instability and ankle osteoarthritis. 2-10 However, the role and the influence of the ST joint on hindfoot disease and instability is still unclear. Our data suggest that the function and the compensatory role of the ST joint could highly depend on the orientation and the shape of the articular surface. This is important to know, since hindfoot osteotomies not only affect the tibiotalar joint but also the ST joint. We strongly believe that the ankle and the ST joint are intimately linked and thus some of the failures in reconstructive hindfoot surgery may be due to the ST joint configuration.

To our knowledge, this is the first weightbearing CT study describing the ST joint configuration on an asymptomatic cohort. A high number of patients were included in attempt to be representative of the general population. A reliable and reproducible angle independent of the long axis of the tibia to determine the inclination of the ST joint was used. 26 The CT scans used in our study presented several advantages: the images collected, with patients being in an upright, weightbearing position, resembled the physiological situation of how the ST joint is normally stressed. The image quality of the portable extremity CT scanner was considered excellent, according to Martinez et al, 21 and furthermore, the detail and accuracy of CT provides the best method nowadays for evaluating hindfoot pathology and alignment. 5

Nevertheless, this study presented some limitations. Although full weightbearing CT scans have the advantage of being high resolution images where the ST joint can be scanned in a loaded, upright position and thus under physiological stress, it is a new method for examining the foot, and thus little previous data are available. 3 Therefore, no comparison can be made with our results. Furthermore, although we included only patients without hindfoot and ankle pathology, we did not take into consideration objective data such as the radiological inclination of the tibial plafond and/or the hindfoot alignment as an exclusion criterion. The reliability of the SVA angle was measured in simulated weightbearing position in a previous study and not in a true upright position as in our study. 26 This could be a potential bias. Instead of the radiation exposure estimated at 12.6 μSv, which was widely lower than the maximal limit of radiation exposure allowed for diagnostic use, this exposure presented a risk potential for asymptomatic volunteers.

In conclusion, a majority of the asymptomatic patients had a concave shaped ST joint in a valgus orientation in the coronal plane. However, variations were found and may have a significant impact on the biomechanics of both the hind- and the midfoot. For the authors, the data suggest that the morphology of the posterior facet may be more involved in hindfoot pathologies than previously expected.

Declaration of Conflicting Interests
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References


CT arthrography of the wrist using a novel, mobile, dedicated extremity cone-beam CT (CBCT)

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Abstract

Purpose To evaluate the feasibility and intra- and interobserver agreement of CBCT arthrography of wrist ligaments, triangular fibrocartilaginous complex (TFCC), and to assess the sensitivity (SE), specificity (SP), accuracy (ACC), and positive and negative predictive value (PPV, NPV) of CBCT arthrography in the diagnosis of scapholunate (SLL) and lunotriquetral (LTL) ligament tears, TFCC, and cartilage abnormalities of the scaphoid and lunate with their corresponding radial surfaces (scaphoid and lunate fossa) using a novel, mobile, dedicated extremity CBCT scanner.

Materials and methods Fifty-two consecutively enrolled subjects (26 M, 26 F, mean age 38 years, range 18–66 years) with suspected wrist ligament tears underwent CBCT-arthrography before normally scheduled MR arthrography. An extremity CBCT was used for imaging with isotropic voxel size of 0.4 × 0.4 × 0.4 mm³. Subsequent routine 1.5 T MRI was performed using a dedicated wrist coil. Two observers reviewed the anonymized CBCT images twice for contrast enhancement (CE) and technical details (TD), for tears of the SLL, LTL, and TFCC. Also, cartilage abnormalities of the scaphoid and lunate with their corresponding radial surfaces (scaphoid and lunate fossa) were evaluated. Inter- and intraobserver agreement was determined using weighted kappa statistics. Since no surgery was performed, MRI served as a reference standard, and SE and SP, ACC, PPV, and NPV were calculated.

Results Intra- and interobserver kappa values for both readers (reader 1/reader 2; first reading/second reading) with 95 % confidence limits were: CE 0.54 (0.08–1.00)/ 0.75 (0.46–1.00); 0.73 (0.29–1.00)/ 0.45 (0.07–0.83), TD 0.53 (0.30–0.88)/ 0.86 (0.60–1.00); 0.56 (0.22–0.91)/ 0.67 (0.37–0.98), SLL 0.59 (0.25–0.93)/ 0.66 (0.42–0.91); 0.31 (0.06–0.56)/ 0.49 (0.26–0.73), LTL 0.83 (0.66–1.00)/ 0.68 (0.46–0.91); 0.90 (0.79–1.00)/ 0.48 (0.22–0.74); TFCC (0.72–1.00)/ (0.79–1.00); 0.65 (0.43–0.87)/ 0.59 (0.35–0.83), radius (scaphoid fossa) 0.45 (0.12–0.77)/ 0.64 (0.31–0.96); 0.58 (0.19–0.96)/ 0.38 (0.09–0.66), scaphoid...
0.43 (0.12–0.74)/ 0.76 (0.55–0.96); 0.37 (0.00–0.75)/ 0.32 (0.04–0.59), radius (lunate fossa) 0.68 (0.36–1.00)/ 0.42 (0.00–0.86); 0.62 (0.29–0.96)/ 0.51 (0.12–0.91), and lunate 0.53 (0.16–0.90)/ 0.68 (0.44–0.91); 0.59 (0.29–0.88)/ 0.42 (0.00–0.84), respectively.

The overall mean accuracy was 82–92 % and specificity was 81–94 %. Sensitivity for LTL and TFCC tears was 76–83, but for SLL tears it was 58 %. For cartilage abnormalities, the accuracy and negative predictive value were high, 90–98 %.

Conclusions A dedicated CBCT extremity scanner is a new method for evaluating the wrist ligaments and radiocarpal cartilage. The method has an overall accuracy of 82–86 % and specificity 81–91 %. For cartilage abnormalities, the accuracy and negative predictive value were high.

Keywords Wrist · Arthrogram · Cone beam CT · Trauma · Musculoskeletal

Introduction

Magnetic resonance arthrography is an established technique for detecting ligament and cartilage injuries of the wrist [1–3]. However, the technique is rather expensive and time-consuming, and MRI in general has several contraindications. Also, spatial resolution of MRI can be a limiting factor, especially in areas of convex or concave joint facets with thin cartilage [4, 5]. Therefore, alternative techniques such as CT arthrography (CTA) have received more attention [6]. CTA is a much faster technique and has excellent spatial resolution [7]. Moreover, the ability for multiplanar reformats makes it even more versatile. In addition to conventional CT scanners, cone-beam CT (CBCT) has been used for dental imaging since the late 1990s [8, 9]. The clinical indications include dentoalveolar imaging, such as assessing dentoalveolar trauma and preoperative assessment of impacted teeth, and preoperative planning for maxillofacial surgery [10]. This method has recently been implemented in orthopedic imaging to study finger and wrist fractures and scaphoid fracture after screw fixation [11, 12]. More recently, dedicated extremity CBCT scanners have been introduced [13, 14]. This application offers an attractive alternative, with high spatial resolution, easy installation, and low radiation dose [4, 11–15] compared to conventional CT scanners. Also, the ability to image the lower extremity during weight bearing, i.e., while the patient stands, opens new possibilities to study degenerative joint disease of the knee, ankle, and foot (Tuominen et al., Weight bearing CT-imaging of the lower extremity, unpublished).

In this study, we wanted to expand the dedicated extremity CBCT scanner’s capabilities even further, i.e., with CT arthrography. Therefore, the purpose of this study was to evaluate the feasibility and intra- and interobserver agreement of CT arthrography of scapholunate and lunotriquetral ligaments, triangular fibrocartilaginous complex, and cartilage abnormalities using a novel, dedicated extremity CBCT. To our knowledge, this is the first report of wrist arthrography using a dedicated extremity CBCT scanner.

Materials and methods

Fifty-three consecutively enrolled subjects were offered a CBCT arthrogram immediately prior to their routinely

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**Fig. 1** CBCT image (88 kVp, 8 mA) of six phantoms of 2-ml volume with varying proportions of 240 mg I/ml iohexol and 2.5 mmol/l tetraazacyclododecanetetraacetic acid (DOTA)-gadolinium in the following respective proportions: 1 phantom 1,100 %/0 %; phantom 2, 75 %/25 %; phantom 3, 50 %/50 %; phantom 4, 25 %/75 %; phantom 5, 0 %/100 %, and phantom 6 100 % isotonic NaCl. Using the mixture of 50/50 (3), there was no decrease in attenuation values as there was with the concentration of 25/75 (4).

**Fig. 2** The hand and wrist can be placed freely in any desired position.
scheduled MRI arthrogram. The time period was 7 months, from November 2010 to May 2011. One patient refused to participate in the study and hence the final study group was comprised of 52 subjects (26 M, 26 F, mean age 38 years, range 18–66 years). Approval was obtained from the hospital’s ethics committee, and written informed consent was obtained from each subject.

The indication for MR arthrography was suspected scapholunate (SL) ligament tear in 17 subjects, lunotriquetral (LT) ligament tear (n=1), SL and LT ligament tear (n=8), SL and triangular fibrocartilage complex (TFCC) tear (n=2), LT and TFCC tear (n=2), TFCC tear (n=19). In addition, radiocarpal joint cartilage assessment was requested in six cases, and evaluation of distal radioulnar joint (DRUJ) in two cases. Five patients were operated on within the last 12 months (Brunelli’s tenosynosis for scapholunate instability, STT-arthrodesis + TFCC fixation, fixation of distal radius fracture with volar plate (n=2), resection of pisiform bone), and one patient had undergone a diagnostic wrist arthroscopy 12 months earlier. Moreover, one patient had avascular necrosis with fragmentation of the lunate.

Since the patients underwent subsequent MRI arthrography because it provided adequate contrast for both in vitro and in vivo CBCT (Fig. 1) and MR arthrography images.

A mean of 2.2 ml (range 1.5–3.0 ml) of 1:1 solution of 2.5 mmol/l Gd-DOTA and 240 mg I/ml iohexol was injected into the radiocarpal joint under palpation guidance.

A novel extremity CBCT scanner (Planned Verity, Planned Oy, Helsinki, Finland) was used to image the wrist (Fig. 2). The dimensions of the scanner are (L × W × H): 185 × 76 × 160 cm, weight app. 350 kg, maximum power-consumption 1.5 kVA with no external cooling needed. The scanner uses a Toshiba X-ray tube with a tungsten target, anode voltage up to 96 kV, anode current 1–12 mA, dual filtration 0.5 mm-Cu + 2.5 mm-Al, and pulsed X-ray radiation. The scanner has a 20 × 25-cm flat-panel amorphous silicon detector. The field of view (FOV) is approximately 13 × 16 cm, and 300 projection images were acquired over an angle of 210° with a scan time of 18 s and reconstruction time of 30–120 s. The isotropic voxel size was 0.4 × 0.4 × 0.4 mm3. Based on previous tests [14], 88 kVp

| Table 1 | Intra- and interobserver kappa values for readers 1 (R1) and 2 (R2) for contrast enhancement (CE), technical details (TD), for tears of scapholunate (SLL) and lunotriquetral (LTL) ligament, and triangular fibrocartilage complex (TFCC) and for cartilage for scaphoid and lunate with corresponding radial surface. R1.1 and R1.2 denote the first and second reader’s first reading, and R1.2 and R2.2 the second readings, respectively. The 95% confidence intervals are shown in parentheses |
|---------|-------------------------|--------------------------|
|         | Intraobserver | Interobserver |
| CE      | R1 0.54 (0.08–1.00) | R1.1-R2.1 0.73 (0.29–1.00) |
|         | R2 0.75 (0.46–1.00) | R1.2-R2.2 0.45 (0.07–0.83) |
| TD      | R1 0.53 (0.30–0.88) | R1.1-R2.1 0.56 (0.22–0.91) |
|         | R2 0.86 (0.60–1.00) | R1.2-R2.2 0.67 (0.37–0.98) |
| SLL     | R1 0.59 (0.25–0.93) | R1.1-R2.1 0.31 (0.06–0.56) |
|         | R2 0.66 (0.42–0.91) | R1.2-R2.2 0.49 (0.26–0.73) |
| LTL     | R1 0.83 (0.66–1.00) | R1.1-R2.1 0.90 (0.79–1.00) |
|         | R2 0.68 (0.46–0.91) | R1.2-R2.2 0.48 (0.22–0.74) |
| TFCC    | R1 0.86 (0.72–1.00) | R1.1-R2.1 0.65 (0.43–0.87) |
|         | R2 0.91 (0.79–1.00) | R1.2-R2.2 0.59 (0.35–0.83) |
| RADIUS (scaphoid fossa) | R1 0.45 (0.12–0.77) | R1.1-R2.1 0.58 (0.19–0.96) |
|         | R2 0.64 (0.31–0.96) | R1.2-R2.2 0.38 (0.09–0.66) |
| SCAPHOID | R1 0.43 (0.12–0.74) | R1.1-R2.1 0.37 (0.00–0.75) |
|         | R2 0.76 (0.55–0.96) | R1.2-R2.2 0.32 (0.04–0.59) |
| RADIUS (lunate fossa) | R1 0.68 (0.36–1.00) | R1.1-R2.1 0.62 (0.29–0.96) |
|         | R2 0.42 (0.00–0.86) | R1.2-R2.2 0.51 (0.12–0.91) |
| LUNATE  | R1 0.53 (0.16–0.90) | R1.1-R2.1 0.59 (0.29–0.88) |
|         | R2 0.68 (0.44–0.91) | R1.2-R2.2 0.42 (0.00–0.84) |
and 8 mA were used, giving a DAP of 716 mGy cm². The small size enabled the scanner to be installed in the general X-ray room.

After CBCT, the patients were transferred to the MRI suite within 15 min post-injection. For MRI, we used a 1.5-T scanner (Signa HD, GE Medical Systems, Milwaukee, WI, USA) using the following imaging parameters: coronal T1 SE (TR/TE 620/13 ms, slice thickness 2.5 mm/2.7 space, matrix 256 × 192), axial T2 fat-saturated MR images (TR/TE eff. 2800/44 ms, slice thickness 3 mm/3.3 mm space, ETL 8, matrix 320 × 192), and coronal T2 Fat-saturated FSE (TR/TE eff. 2760/68 ms, ETL 10, slice thickness 2.5 mm/2.7 space, matrix 288 × 192). FOV was 10 cm in each sequence.

The images were transferred to a 27” iMac computer (Mac OS 10.6.4, Cupertino, CA, USA) and analyzed using Aycan Osirix Pro (v. 1.3, English Edition, January 2010, Aycan Digital Systems GmbH, Würzburg, Germany) software. Before the final analysis, the studies were anonymized and assigned a random ID number generated using freeware obtained at http://www.random.org/.

A month later, two radiologists with more than 5 years of experience in musculoskeletal (MSK) trauma imaging using CT and MRI reviewed the CBCT images twice with a minimum 2-week interval between evaluations, for contrast enhancement (CE; 1=good, 2=fair; 3=poor) and technical details (TD; 1=good, 2=motion, 3=suboptimal contrast injection). Also, evidence of tears of scapholunate (SLL) and lunotriquetral (LTL) ligaments (1=no tear, 2=completely torn, 3=partial tear) and triangular fibrocartilaginous complex (TFCC) (1=no tear, 2=torn) and cartilage abnormalities (1=normal, 2=thinning, 3=exposed subchondral bone) for scaphoid and lunate with corresponding radial surface (scaphoid and lunate fossa) were evaluated.

For MRI analysis, we used standard clinical workstations (Agfa DS3000, IMPAX 5.3, Agfa-Gaervert, Mortsel, Belgium) with 2-megapixel monitors (Barco Inc., Kortrijk, Belgium).

Inter- and intraobserver agreement was determined using weighted kappa statistics. In this study, it was defined that kappa-values 0.01–0.20 mean slight agreement, 0.21–0.40 fair agreement, 0.41–0.60 moderate agreement, 0.61–0.80 substantial agreement, and 0.80–0.99 almost perfect agreement [16]. Since no surgery was performed, the consensus MRI reading served as a reference standard, and sensitivity (SE), specificity (SP), accuracy (ACC), and positive and negative predictive values (PPV, NPV) were calculated.

Statistical analyses were done using a commercial software package SAS/STAT v.9.2 (SAS Institute Inc., Cary, NC, USA).

Results

Each CBCT imaging study was technically successful. In two patients, the contrast was suboptimal; in one case most likely due to previous fracture fixation, in the other case due to technical difficulties during injection. Also, in two patients with radial volar titanium plate and screws, the metal artifact caused less diagnostic problems in the assessment of both the wrist cartilage and ligament structures in CBCT images compared to the MRI.

Interobserver agreement for SL ligament was fair. Moderate agreement was seen on articular cartilage for radius, scaphoid, and lunate, and substantial agreement for LT
ligament and TFCC. Intraobserver agreement for TFCC was almost perfect (Table 1).

Image quality is demonstrated in Fig. 3.

We found 11 SLL tears (ten total, one partial), seven LTL tears (five total, two partial), and 25 TFCC degenerations or tears according to Palmer classification (type 1A; 16, 1B; 2, 2A; 2, 2B 3; 2C; 2 and 2D 2) (Figs. 4, 5, and 6). For cartilage abnormalities, there were four cartilage abnormalities (thinning or subchondral bone exposure) for radial surface facing scaphoid (scaphoid fossa) and in scaphoid, six in lunate, and five in corresponding radial surface (lunate fossa).

The mean values for SE, SP, ACC, PPV, and NPV for SLL tears were 56, 91, 83, 67, and 89 %; for LTL tears 83, 81, 82, 44, and 96 %; for TFCC tears 76, 90, 87, 83, and 87 %, respectively. The results for each reader are presented in Table 2.

The mean values for SE, SP, ACC, PPV, and NPV for cartilage abnormalities for radial surface facing were 69, 94, 92, 53, and 97 %; for scaphoid 71, 94, 92, 61, and 97 %; for lunate fossa 63, 92, 90, 28, and 98 %; and for lunate 70, 92, 90, 52, and 97 %, respectively. The results for each reader are presented in Table 3.

**Discussion**

CT arthrography is an alternative in patients when MRI is contraindicated or when MRI is not available.
Moreover, multi-detector CT (MDCT) arthrography has been reported to be more accurate than MRI or MR arthrography, especially in detecting partial tears of SL and LT ligaments [6]. In addition, experimental flat-panel C-arm CT arthrography has recently been reported [17]. In the current study, we used a novel, dedicated ambulatory cone-beam CT. Each study was technically successful, with overall accuracy of 82–86 %. This method offers exciting possibilities for orthopedic imaging in general. High spatial resolution, low radiation dose, and easy installation provide a potential one-stop shop for various orthopedic problems, such as subtle fracture detection and post-traumatic evaluation of fracture consolidation, especially when osteosynthetic material has been used [12]. Moreover, this technique allows imaging in a comfortable sitting position or even in patients lying on a hospital bed.

The spatial resolution used (0.4 mm³) is superior to standard MR imaging where slice thickness is usually 2–3 mm and in-plane resolution 0.5–0.7 mm although

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**Fig. 6** SL-tear (arrow) in a 63-year-old male. a Coronal CT-image, b blue line shows the plane to create the axial plane in c. Corresponding coronal fat-saturated T1 SE (TR/TE 620/13 ms, FOV 10 cm, slice thickness 2.5 mm/2.7 space, FOV 10 cm, matrix 256×192 d) and e axial T2 FSE fat-saturated MR images (TR/TE eff. 2800/44 ms, slice thickness 3 mm/3.3 mm space, ETL 8, FOV 10 cm, matrix 320×192). Contrast leakage is seen to midcarpal joint (asterisk; a). No perforation in TFC (arrowhead; a, d) is seen. Note also the excellent visualization of cartilage (block arrow; a), whereas the soft-tissue contrast (c) is sub-optimal compared to MRI (e). Curved arrow in c, e indicates the median nerve.
sub-millimeter isotropic voxels can also be obtained with 3.0-T scanners with gradient echo sequences, such as VIBE (volume interpolated breath-hold examination [18]). However, compared to MRI, the imaging time using CBCT is very short (18-s scan time) and patient positioning is easy, making it less prone to motion artifacts. Moreover, wrist CBCT arthrography could be an alternative in postoperative patients with radial volar plate fixation due to relative absence of metallic artifacts compared to MRI. The spatial resolution of the dedicated extremity CBCT is similar to MDCT scanners. However, due to limitations in low-contrast sensitivity of CBCT due to, e.g., scatter, soft-tissue contrast is lower compared to MDCT data. General challenges in CBCT contrast detectability, including scatter, beam hardening, truncation, and limited number of projections, can be partially corrected with calculation methods as reported for C-arm applications [19]. In the case of wrist imaging with FOV of 13 × 16 cm, the truncation effect is not a concern with the dedicated extremity CBCT.

According to dentomaxillofacial studies, the radiation doses of CBTC examinations are significantly lower compared to conventional MDCT scans [20–23]. The CBCT technique has also been previously used to detect finger fractures with equal accuracy as MDCT but with significantly less radiation [10]. Also, three cases of CBCT imaging of the wrist, including one with intra-articular contrast, has been reported [11]. The scanners used, however, represent a different design and technology than that used in the current study. Due to the target size and geometry of the X-ray beam in the scanner, conventional computed tomography dose index (CTDI) measures are not applicable to estimate the radiation exposure to the patient. Dose area product (DAP) also has limitations because the radiation beam area is wider than the wrist area. For typical exposure values used in the study (88-kV tube voltage, 8-mA tube current), DAP of 716 mGy*cm² was measured. For the wrist imaging, a conversion coefficient of 0.01 mSv/Gy*cm² [22] was used, providing an effective dose estimate of 7 μSv.

### Table 2 Sensitivity (SENS), specificity (SPES), accuracy (ACC), positive predictive value (PPV), and negative predictive value (NPV) for scapholunate (SL), lunotriquetral (LT) ligament, and triangular fibrocartilaginous complex (TFCC) tears for readers 1 and 2. R1.1 and R2.1 denote first and second reader’s first reading, and R1.2 and R2.2 the second readings, respectively.

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### Table 3 Sensitivity (SENS), specificity (SPES), accuracy (ACC), positive predictive value (PPV), and negative predictive value (NPV) for cartilage abnormalities for scaphoid and lunate with corresponding radial surface for readers 1 and 2. R1.1 and R2.1 denote first and second reader’s first reading, and R1.2 and R2.2 the second readings, respectively.

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Skeletal Radiol
The inter- and intraobserver agreement was in most cases substantial. The fair interobserver agreement in SL ligament can be explained by the heterogeneity of our material with a substantial number with previous surgery and still-existing metal implants. In these cases, the distorted anatomy and postoperative changes interfered with the analysis even in retrospect. However, the study group was comprised of unselected material and is representative of a typical busy orthopedic practice. Also, the differences between readers most likely reflect the personal differences. In order to increase the specificity, reader 1 has, in general, lower sensitivity, and if the number of pathologic conditions is small, e.g., five in cartilage in lunate fossa (Table 3), one discordant reading may lead to substantial change in sensitivity. In addition, with an increasing prevalence, the values of the sensitivity and specificity of both observers have to increase in order to maintain a certain kappa value [24]. Therefore, a low kappa value, combined with a high prevalence of one of the categories, cannot be interpreted easily, and in such a case, the number of observations should be extended to make the prevalence of the categories more equally distributed [24].

The visualization of cartilage surface was excellent (Fig. 3), and provides a potentially good method of detecting cartilage injuries in the radiocarpal as well as other small joints, where cartilage thickness is in the order of 1 mm or less. While MR arthrography is good for detecting cartilage defects [25], arthroscopy is needed for a reference standard. It should be noted, however, that in case of orthopedic hardware, the visualization of cartilage with CBCT was better than with MR arthrography (Fig. 7).

In a previous study, CT arthrography was shown to have a very high (>90 %) sensitivity and specificity for SL, LT, and TFCC tears [6]. In our study, the corresponding numbers were slightly smaller, probably reflecting differences in the study population. They were also able to study partial tears, whereas in our study the amount of partial tears as well as the cartilage abnormalities was too small for a more detailed analysis.

The dedicated extremity CBCT scanner’s low radiation dose, easy installation, and easy use open new possibilities for imaging of the radiocarpal joint. The use of CBCT arthrography and subsequent MR arthrography combines the inherent strengths of both methods; excellent visualization of bony structures and soft tissue contrast, respectively. Concomitant reading of both studies would potentially lead to increased diagnostic confidence and performance.

CT arthrography is recommended together with MR arthrography in order to increase the diagnostic accuracy of foveal tears and to assess the associated bone fragments [26].

Fig. 7 In a patient with volar radial plate, ligament structures (SL-ligament; asterisk), wrist cartilage surface (especially in lunate, arrowhead) and a scaphoid cartilage defect (arrow) are better delineated on the coronal CT-image due to fewer metal artifacts (a) compared to corresponding T1-w fat-saturated SE MR image (b)

In conclusion, the dedicated CBCT extremity scanner is a new method for evaluating wrist ligaments. Moderate agreement was seen on articular cartilage for radius, scaphoid and lunate, and substantial agreement for LT ligament and TFCC. Interobserver agreement for SL ligament was fair. Intraobserver agreement for TFCC was almost perfect. The method has an accuracy of 82–86 % and specificity of 81–91 %. Sensitivity for LT and TFCC tears was 77–83 %, but for SLL tears it was 58 %. For cartilage abnormalities, the accuracy and negative predictive value were high, 90–98 %.
Acknowledgments  Sharon J. Kuong, MD, is acknowledged for her linguistic help.

Conflict of interest  The authors acknowledge that within the past 3 years they have received benefits which might result in a conflict of interest or the appearance of a conflict. Nature of benefit: Research Consultants (authors 1,3–5,7), employment (author 6).

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