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Ankle morphometry based on computerized tomography

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ABSTRACT

Background: Thorough understanding of the morphometry of the ankle joint is crucial to optimize conservative and operative therapy of ankle joint disorders. Despite recent improvements, basic anatomic and biomechanical correlations of the ankle joint including the orientation of the ankle joint axis and joint morphology as its key biomechanical features are not sufficiently recorded to date. The aim of this study was the evaluation of the ankle morphometry to gain information about the ankle joint axis.
Material and methods: In this study 98 high-resolution CT-scans of complete Caucasian cadaver legs were analysed. Using the software Mimics and 3-Matic (Materialize) 22 anatomic parameters of the talocrural joint were assessed, including the length, width and surface area of the tibial and talar articular areas. Additionally, the radii of the articular areas, the medial distal tibial angle and the height of the talar dome were determined.
Results: The radius of the central trochlea tali was 44.6 ± 4.1 mm (mean ± SD). The central trochlea tali arc length was 40.8 ± 3.0 mm and its width was 27.4 ± 2.5 mm. Additionally we determined 47.0 ± 4.4 mm for the tibial sagittal radius, 27.6 ± 3.0 mm for the tibial arc length and 27.4 ± 2.5 mm for the central tibial width.
Conclusion: The present study describes the three-dimensional morphometry of Caucasian ankle joints in detail. This dimensional analysis of the ankle joint will inform the development and placements of implants and prostheses.

1. Introduction

A detailed knowledge of anatomy and biomechanics of the ankle joint is crucial to optimize treatment [1–3]. In cases of ankle joint fractures this knowledge is necessary for reconstruction of ankle joint line [4]. Furthermore in treatment of severe osteoarthritis, potential combined deformities need additional consideration. Examples are supramalleolar osteotomies as they aim to correct the medial distal tibial angle as well as the distal tibal slope to optimize loading. Additionally, in the non joint preserving procedure ankle joint arthrodesis, the consideration of foot positioning in all planes is important [3,5–10]. The importance of anatomic and biomechanical correlations is even higher in total ankle replacement (TAR). The prosthesis design requires the knowledge of the anatomy. Additionally ankle joint anatomy and biomechanics predict prosthesis placement [11–14]. However, until know there is no consensus about the ankle rotational axis [15–27].

For the evaluation of anatomy *in vitro* measurementps with cadavers are described as well as *in vivo* measurements based on imaging modalities. Most previous studies regarding the anatomy of the ankle joint were based on conventional radiographs already including evaluation of the widths, lengths and radii of the talar and tibial articular surfaces [28–32]. And whereas Hayes et al. presented initially three-dimensional data of the ankle joint still there is a lack of information about relevant anatomic parameters like length of the talar articular surface, the radius in different

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sagittal sections and Hayes did not analyze the distal tibia with its articular surface [33].

The aim of the present study was the determination of ankle morphometry by high-resolution computer tomography (CT) to improve the understanding of the joint biomechanics.

2. Material and methods

2.1. Cadaver and segmentation

The present study was based on 98 CT scans of full Caucasian cadaver legs including the femoral head. The cadavers were fixed in formalin. The mean age was 81 (range: 44–104) years, 50 legs were from female patients and 48 from male patients. Specimens with obvious previous trauma, severe deformity or severe degenerative changes in any joint of the leg defined by a Kellgren and Lawrence score of >3 were excluded from analysis [34]. Previous trauma was excluded via the absence of fracture lines, callus formation or cortical inhomogenities. Severe degenerative changes were analyzed based on the Kellgren and Lawrence criteria including osteophytes, subchondral sclerosis and cysts [34]. Additional detailed information was included in our previous publication [35]. We imported all scans into Mimics® (Version 20.0, Materialise©, Leuven, Belgium) and resliced them applying the coordinate system recommended by the International Society of Biomechanics (ISB) (Fig. 1) [36].

2.2. Basic anatomic data

We assessed basic anatomic data regarding the talocrural joint in the sagittal, torsional and axial plane with Mimics®. The parameters were chosen orientated to a previous publication of Kuo et al. [37].

In the sagittal plane tibial arc length (TiAL), radius of the tibial joint surface (TiSR), maximal tibial thickness (MTiTh), anterio-posterior gap (APG), anterio-posterior angle (APA), trochlea tali arc length (TaAL), trochlea tali arc radius (TaR), talus height (TaH) and the distance between the tibial and talar subchondral cortices (SDTaTi) were measured (Fig. 2). Angles determined in the sagittal plane orientated anterior-proximal are positive, dorsal-proximal are negative.

In the torsional plane tibial width (TiW), malleolar width (MalW), medial distal tibial angle (MDTA), the angle between the mechanical tibial axis and the line connecting the most inferior points of the fibula and tibia (MLATi), the angle between the mechanical tibial axis and the line connecting the most medial and lateral point of the trochlea tali joint surface (MLATa), the trochlea tali width (TaW) and the mechanical tibiofemoral angle were measured (Fig. 2). Angles measured in the torsional plane orientated to medial-proximal are positive, to lateral-proximal are negative.

Moreover, in the axial plane the tibial cross sectional area (TiCA) and talar cross sectional area (TaCA) were measured (Fig. 2).

2.3. Statistical analysis

The statistical analysis was performed with IBM SPSS Statistics© (Version 24.0, IBM©, Armonk, New York 10504). A two-sided unpaired Student's t-test was used for data on interval scale. The values are expressed as mean with standard deviation, p-values with $p < 0.05$ being significant.

3. Results

In sagittal plane we found an overall TiAL of 27.6 ± 3.0 mm and a central TaAL of 40.8 ± 3.0 mm. The corresponding central widths of

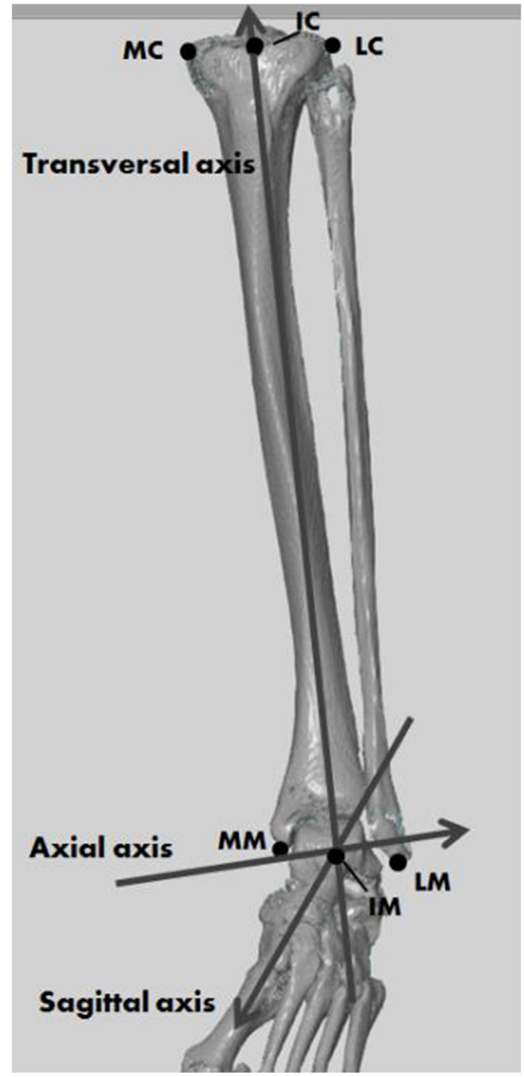

Fig. 1. Coordinate system.

the articular surfaces were 27.4 ± 2.5 mm for the tibia and 28.1 ± 2.7 mm for the talus. Evaluating differences between female and male legs we found relevant differences for TiSR, MTiTh, TaAL, TaR, TiW, MaLW, TaW and TaCA (Table 1).

4. Discussion

The present study presents a detailed three-dimensional analysis of the ankle joint anatomy of Caucasians.

This study was based on CT-scans as these allow detailed information of the bony configuration, are widely available and fast to acquire and are therefore less prone to movement artifacts compared to MRI. Further on as the cartilage layer of the ankle joint is very homogenous and thin with a mean cartilage thickness of the talar articular surface of 1.1 mm and of the tibial articular surface of 1.16 mm [38], conclusions on the joint anatomy can be drawn.

Most previous studies were based on plain radiographs. The advantages of CT scans compared to plain radiographs are that they provide detailed three-dimensional information with a high resolution are not are not as susceptible as plane radiographs to radiologic enlargement, parallax errors, ankle position and rotation of the shank [3,31]. To our best knowledge only two previous studies analyzed the ankle anatomy in CT studies. Hayes et al. analyzed only 21 Caucasian patients and presented with the width and the radius of

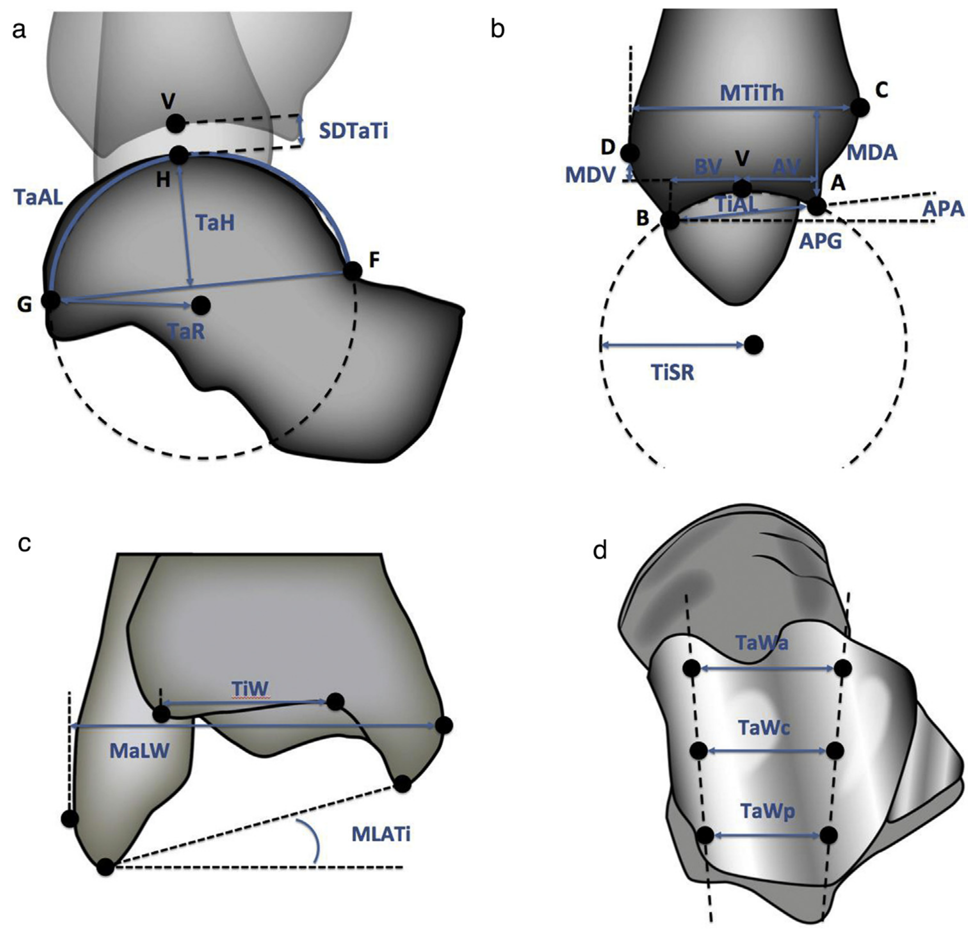

Fig. 2. Illustration of the evaluated anatomic parameters based on Kuo et al. [37].
The evaluated parameters assessed in sagittal plane are illustrated in a) and b), torsional plane in c) and axial plane in d).

the talar articular surface a limited number of parameters [33]. Kuo et al. analyzed 58 Chinese specimens. Therefore our study is the largest, detailed study on a Caucasian population.

For segmentation and analyses we used the established products of Materialise© likewise to previous authors [11,17,19,40–44]. This enables to reslice the CT scans regarding to the coordinate system, generates three-dimensional models and provides the analysis tools needed for the present study. Based on a publication of Kuo et al. the use of a high number of anatomic parameter provides a detailed description of the ankle joint anatomy [37].

We compared our findings with Kuo's of Chinese ankle joints [37]. Whereas TiCA showed no relevant difference, we found a slightly smaller TiAL of 27.6 mm ± 3.0 compared to 28.4 mm ± 2.9 whereas our TiSR was higher with 47.0 ± 4.4 compared to 26.1 ± 4.0. Likewise our TiWa was lower with 28.7 mm ± 2.5 compared to 33.3 mm ± 2.5. One reason for this difference might be that we included a higher rate of female cadaver legs. However the respective values of the isolated analysis of male and female legs showed the same tendency. There were only slight differences regarding the parameters MTiTh, APG, MDA, MDV. The TiPD in our study was higher illustrating that the highest point of the tibial articular surface is more anterior in our cohort than in a Chinese population. Our SDTaTi was low with 2.7 mm ± 0.6 consistent with the known fact of the high congruency of the ankle joint and the consecutive lower thickness of cartilage layer.

Interestingly we found higher values for talar anatomic parameters. The TaALm was slightly higher with 38.9 mm ± 9.9 (vs. 33.5 mm ± 4.9), the TaRc was 44.6 mm ± 4.1 (vs. 21.8 mm ± 2.0) and the TaWc was 28.1 mm ± 2.7 (vs. 20.9 ± 3.0). In correlation we had a higher TaCA with 1265 mm^2 ± 206.4 compared to Kuo et al. whereas this is not absolutely comparable as we used a different plane. Noteworthy there was no relevant difference of the TaH (13.6 mm ± 2.0 vs. 11.9 mm ± 1.8). Regarding MLaTa und MLaTi there were no relevant differences when transforming our values to the measured direction of Kuo et al.

Compared to the three-dimensional data of Hayes et al. we found a higher TaR whereas there was no relevant difference regarding the TaW [33]. The comparability of our data to two-dimensional data is limited. Still we found no relevant differences regarding TiAL, APG, APA, MDA, MDV, MTiTh and TaH but a higher TiSR and a lower TiW compared to previous data from Stagni et al. and Fessy et al. However whereas Kuo et al. described lower values of TaAL and TaW for their Chinese population our data for these parameters are in accordance to the presented two-dimensional data of Stagni et al. and Fessy et. al. for a Caucasian population [28,29,37].

Our study has some limitations. We were not able to provide information about the height and weight of the patients and thus could not correlate this to the ankle findings. However, relevant degenerative changes and previous trauma were excluded prior to evaluation. Our CT scans were done in formal fixed cadavers which might have affected the configuration of the anatomy, although this has not been reported before. The CT scans were not taken weightbearing. But this only would have been relevant if the configuration of the joints or bones to each other would have been

Table 1
Results of the anatomic parameters.
The results of all scans and an itemized analysis of female vs. male legs is provided.

	All (n = 96)			Male (n = 48)			Female (n = 50)			
	Mean	SD	95% CI	Mean	SD	95% CI	Mean	SD	95% CI	*p-value*
TiAL (mm)	27.6	3.0	27.0–28.2	29.3	2.4	28.6–30.1	26.0	2.3	25.3–26.7	*n.s.*
TiSR (mm)	47.0	4.4	46.1–47.9	49.5	4.1	48.1–50.8	45.1	3.5	44.0–46.1	$p < 0.05$
MTiTh (mm)	40.8	3.1	40.1–41.4	43.4	1.9	42.8–44.0	38.8	1.9	38.2–39.4	$p < 0.05$
APG (mm)	2.0	1.4	1.7–2.3	2.1	1.6	1.6–2.6	2.0	1.3	1.6–2.3	*n.s.*
APA (deg)	3.7	3.3	3.1–4.2	3.8	3.6	2.7–4.9	3.9	3.2	3.0–4.9	*n.s.*
MDA (mm)	10.8	1.7	10.5–11.2	11.0	1.8	10.5–11.6	10.8	1.8	10.2–11.3	*n.s.*
MDV (mm)	4.8	1.9	4.4–5.2	5.0	1.9	4.4–5.6	4.4	1.7	3.7–4.7	*n.s.*
TiPD (%)	96.6	14.9	93.5–99.6	100.1	15.8	95.0–105.1	94.6	13.8	90.4–98.8	*n.s.*
TaAL*m* (mm)	38.9	9.9	38.1–39.7	40.7	3.4	39.6–41.7	36.8	3.3	35.7–37.8	$p < 0.05$
TaAL*l* (mm)	40.5	3.7	40.7–41.2	42.2	2.3	41.5–43.0	38.5	3.7	37.4–39.6	$p < 0.05$
TaAL*c* (mm)	40.8	3.0	40.2–41.4	42.4	2.3	41.7–43.2	39.1	2.6	38.3–39.8	$p < 0.05$
TaR*m* (mm)	42.9	4.5	42.0–43.8	45.2	4.8	43.7–46.8	40.5	3.0	39.6–41.4	$p < 0.05$
TaR*l* (mm)	45.2	4.3	44.3–46.1	47.4	3.5	46.2–48.5	42.3	3.9	41.7–44.1	$p < 0.05$
TaR*c* (mm)	44.6	4.1	43.8–45.5	47.1	4.3	45.7–48.5	42.5	2.7	41.6–43.3	$p < 0.05$
TaH (mm)	13.6	2.0	13.2–14.1	13.8	2.1	13.1–14.5	13.1	1.8	12.5–13.6	*n.s.*
SDTaTi (mm)	2.7	0.6	2.5–2.8	2.8	0.5	2.6–3.0	2.6	0.5	2.4–2.7	*n.s.*
TiW*a* (mm)	28.7	2.5	28.2–29.2	30.0	2.1	29.4–30.7	27.8	2.0	27.2–28.4	$p < 0.05$
TiW*p* (mm)	25.1	3.3	24.5–25.8	27.3	2.7	26.4–28.2	23.7	2.3	23.0–24.4	$p < 0.05$
TiW*c* (mm)	27.4	2.5	26.9–27.9	28.9	2.3	28.1–29.5	26.4	1.7	25.8–26.9	$p < 0.05$
MaLW (mm)	68.1	4.3	67.2–69.0	71.7	3.0	70.8–72.7	64.8	2.4	64.1–65.6	$p < 0.05$
MDTA (deg)	88.2	2.5	87.7–88.7	88.4	2.4	87.7–89.2	88.3	2.5	87.6–89.1	*n.s.*
MLATi (deg)	77.1	2.8	76.5–77.7	76.1	2.4	75.4–76.9	77.8	2.9	76.9–78.7	*n.s.*
MLATa (deg)	88.8	3.2	87.9–89.8	89.8	2.8	88.9–90.7	88.0	3.4	87.0–89.0	*n.s.*
TaW*a* (mm)	30.2	3.0	29.5–30.8	31.8	2.7	31.0–32.7	28.5	2.6	27.7–29.3	$p < 0.05$
TaW*p* (mm)	22.3	3.0	21.7–22.9	23.6	3.2	22.6–24.6	21.0	2.2	20.4–21.7	$p < 0.05$
TaW*c* (mm)	28.1	2.7	27.5–28.6	29.3	2.6	28.5–30.1	26.7	2.2	26.0–27.3	$p < 0.05$
Var/Val (deg)	1.0	3.6	0.3–1.8	1.1	4.2	0.2–2.6	1.8	2.4	1.0–2.6	*n.s.*
TiCA (mm^2)	738.6	101.9	717.6–759.6	797.8	101.2	765.5–830.2	687.3	70.1	666.0–708.7	*n.s.*
TaCA (mm^2)	1265	206.4	1223–1308	1419	156.9	1369–1469	1128	147.3	1083–1173	$p < 0.05$

analyzed. Due to the high congruency of the ankle joint, relevant influences of joint position on the measurements would not be expected.

The strengths of the present study were, first, the use of a coordinate system based on ISB recommendations. Thereby we applied a standardized and validated system as used by several authors [17,23,25,36,39]. Second the high number of used cadaver legs compared to previous studies and the high number of anatomic parameters leading to a detailed description of the ankle joint anatomy. However we found relevant interindividual differences of basic anatomic parameters in accordance with described high interindividual differences of the ankle joint morphometry [16,21,25]. Moreover, especially osteoarthritic ankles undergo structural changes, leading to individual composition of bone and ligaments [45]. This supports the clinical relevance of the present study highlighting the potential need of patient oriented specific implantation techniques of TAR. Regarding the found intersexual differences gender specific implants might be discussed. Whereas in total knee arthroplasty gender specific implants showed no relevant benefit, the related discussions and evaluations led to modifications of prosthesis design [46–49]. This could be of benefit in TAR as well.

5. Conclusion

This study describes the radiologic ankle anatomy in a Caucasian population based on CT data. Intersex differences might be relevant in TAR design. Further on relevant interindividual difference were found, so a preoperative planning based on CT data might help to optimize fracture treatment, planning of corrective osteotomies as well as fit and placement of TAR components.

Further studies are necessary to evaluate the correlation of these parameters with the ankle joint axis.

Conflict of interest statement

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