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SCIENTIFIC ARTICLE

Torque application helps to diagnose incomplete syndesmotic injuries using weight-bearing computed tomography images

Nicola Krähenbühl [1] · Travis L. Bailey [1] · Angela P. Presson [2] · Chelsea McCarty Allen [2] · Heath B. Henninger [3] · Charles L. Saltzman [1] · Alexej Barg [1]

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Abstract

Objective Accurate identification of distal tibio-fibular syndesmotic injuries is essential to limit potential deleterious post-traumatic effects. To date, conventional radiographs, computed tomography (CT), and magnetic resonance imaging (MRI) have shown limited utilization. This cadaver study evaluates the utility of weight-bearing CT scans on the assessment of incomplete and more complete syndesmotic injuries.

Materials and methods Ten male cadavers (tibial plateau to toe-tip) were included. Weight-bearing CTs were taken under four test conditions, with and without torque on the tibia (corresponding to external rotation of the foot and ankle). First, intact ankles (native) underwent imaging. Second, the anterior–inferior tibio-fibular ligament (AITFL) was transected (condition 1). Then, the deltoid ligament (condition 2) was transected, followed by the interosseous membrane (IOM, condition 3). Finally, the posterior–inferior tibio-fibular ligament (PITFL) was transected (condition 4). The medial clear space (MCS), the tibio-fibular clear space (TFCS), and the tibio-fibular overlap (TFO) were assessed on digitally reconstructed radiographs (DRRs), and on axial CT images.

Results The TFO differentiated isolated AITFL transection from native ankles when torque was applied. Also under torque conditions, the MCS was a useful predictor of an additional deltoid ligament transection, whereas the TFCS identified cadavers in which the PITFL was also transected.

Conclusion Torque application helps to diagnose incomplete syndesmotic injuries when using weight-bearing CT. The TFO may be useful for identifying incomplete syndesmotic injuries, whereas the MCS and TFCS predict more complete injuries.

Keywords Imaging · Weight-bearing CT · Syndesmotic injury · Deltoid ligament injury

Introduction

Accurate identification of distal tibio-fibular syndesmosis injuries is difficult, especially in the absence of frank bony diastasis [1–3]. Reports in literature suggest that missed injuries might lead to chronic pain and early degeneration of tibiotalar articulation [4, 5]. Currently, the initial diagnosis of syndesmotic disruption is based on several radiographic parameters [1]. Measurement of the medial clear space (MCS), tibio-fibular clear space (TFCS), and the tibio-fibular overlap (TFO) on external stress ankle radiography has high specificity yet low sensitivity [1, 6]. Magnetic resonance imaging (MRI) has also been shown to aid diagnosis; however, this nonweight-bearing modality fails to illustrate the dynamic relationship between the tibia and fibula when load and torque are applied to the ankle [1, 7–9].

The anatomical relationship within the distal tibio-fibular syndesmosis is highly complex and relies on four main ligaments to maintain congruity: the anterior–inferior tibio-fibular ligament (AITFL), interosseous membrane (IOM), posterior–inferior tibio-fibular ligament (PITFL), and transverse tibio-fibular ligament (TTFL) [10]. Additionally, medial ankle support via the deltoid ligament is thought to play a pivotal role

Investigation performed at the University of Utah, Salt Lake City, Utah, USA

✉ Alexej Barg
alexej.barg@hsc.utah.edu

1 Department of Orthopaedics, University of Utah, 590 Wakara Way, Salt Lake City, UT 84108, USA

2 Division of Epidemiology, Department of Internal Medicine, University of Utah, 295 Chipeta Way, Salt Lake City, UT 84108, USA

3 Orthopaedic Research Laboratory, University of Utah, 590 Wakara Way, Salt Lake City, UT 84108, USA

[11]. The entire complex is subject to acute and chronic structural changes from repeated stresses seen during daily ambulation or secondary to acute injury [12]. An appropriate understanding of how these structures interact and react under stress is essential to our understanding of pathological conditions.

First described in 1998, cone beam computed tomography (CT) utilization has steadily increased since its introduction in the orthopedic literature in 2013 [13, 14]. Weight-bearing CT offers a precise representation of bony architecture under physiological loads in addition to the resultant change in biomechanics incurred during injury [15]. The purpose of this cadaver study was to assess whether weight-bearing CT scans can be used to identify subtle and also more severe injuries to the distal tibio-fibular syndesmosis using three commonly used measurement options.

Materials and methods

Data source

This study was performed under the University of Utah Institutional Review Board exemption protocol #11755. Ten different male cadavers (tibial plateau to toe-tip; 7 left, 3 right) were included (mean age 63 ± 9 [range 47–70] years; mean weight 83.1 ± 13.5 [range 63.5–104.8] kg; mean BMI 26.3 ± 3.8 [range 20.1–32.3] kg/m^2). The cadavers were provided by United Tissue Network (Norman, OK, USA) and Science Care (Phoenix, AZ, USA). Inclusion criteria were age 20 to 70 years and a body mass index (BMI) of less than 35 kg/m^2. To ensure a homogeneous cohort, only male cadavers were included. Exclusion criteria were a history of any foot and ankle injuries, or a history of surgery of the foot and ankle.

Experiments

Before any experiments were performed, each specimen was thawed for at least 24 h at room temperature [16]. A radiolucent frame consisting of a base plate and four pillars located on the lateral sides of the foot was created to hold the specimens in a plantigrade position (Fig. 1). Each cadaver was fixed with an Ilizarov apparatus (using four 1.5-mm Kirschner-wires [K-wires] drilled through the tibia) that fitted into the frame. K-wires were tightened using a Dynamometric Wire Tensioner (Smith & Nephew). The hindfoot was fixed using two 1.5-mm K-wires drilled through the calcaneus. In addition, a two-part resin (Bondo®, 3 M) was used to stabilize the hindfoot.

Intact ankles (native) underwent imaging first. Then, each ankle underwent AITFL transection (condition 1). The deltoid ligament was transected next (condition 2), followed by the IOM (condition 3), and the PITFL (condition 4). Transection of the deltoid ligament included the tibio-navicular and tibio-spring ligaments. Then, the tibio-calcaneal ligament was transected. Finally, the anterior and posterior parts of the deep deltoid ligament were transected under visual control. Whereas conditions 1 and 2 mimic incomplete injuries, conditions 3 and 4 mimic more complete injuries to the distal tibio-fibular syndesmosis.

Weight-bearing (85 kg; determined by the average specimen weight) CTs with and without application of 10 Newton meters (Nm) of internal rotation torque applied at the Ilizarov apparatus (corresponding to external torque of the foot and ankle) were performed (pedCAT; CurveBeam, Warrington, PA, USA, medium view, 0.3-mm slice thickness, 0.3-mm slice interval, kVp 120, mAs 22.62) [12]. Before the experiments were performed, preconditioning of the specimens was done by loading the frame with 42.5 kg and 85 kg for 2 min each.

Imaging and measurements

Digitally reconstructed radiographs (DRRs) were reconstructed automatically using the CT dataset (CurveBeam, version 3.2.1.0). Previous research showed that measurements on DRRs were comparable with conventional radiographs [15]. As conventional radiographs are still the standard imaging modality for assessing syndesmotic injuries, this approach provides additional information regarding the impact of torque on measurements when using conventional radiographs. The antero-posterior (AP) view of the ankle joint was generated perpendicular to a longitudinal axis of the foot [17, 18]. The mortise view was generated by virtually internally rotating the foot until a symmetrical widening of the medial and lateral gutters was visible [19]. As torque has an impact on talar rotation, it is difficult to reconstruct a mortise view under torque conditions [20]. Therefore, the same degree of internal rotation under native conditions was used for reconstruction of a mortise view from an AP view in the same specimens while under torque loading. The TFCS and the TFO were measured 1 cm above, and the MCS 1 cm below, the medial edge of the distal tibial plafond on both AP and mortise views (Fig. 2) [21, 22].

Computed tomography 1 cm above the medial edge of the distal tibial plafond (axial images) was reconstructed at the highest point of the distal tibial plafond on the sagittal view and used for measurements of the TFO and the TFCS (Fig. 2) [23]. CTs 1 cm below the medial edge of the distal tibial plafond (axial images) were additionally reconstructed. Those images were used for measurement of the MCS (Fig.

2). The MCS was defined as the distance between the most anterior articular surface of the medial malleolus to the talus.

Statistical analysis

Intraclass correlation coefficients (ICCs) were used to quantify the agreement of measurements between and within observers. Estimates and 95% confidence intervals (CIs) were calculated for each type of measurement within each view. Inter-observer agreement was modeled with a two-way random effects model of absolute agreement with a single measurement per observation, defined as ICC(2,1). Intra-observer agreement was modeled with a two-way mixed effect model of consistency with a single measurement per observation, defined as ICC(3,1). Agreement was rated as very good (ICC > 0.80); good (ICC = 0.61–0.80); moderate (ICC = 0.41–0.60); fair (ICC = 0.21–0.40); and poor (ICC < 0.20) [24]. Measurements for inter-observer agreement calculation were carried out by a physician (NK) and a research analyst (MWW). For calculation of the intra-observer agreement, measurements were performed by a physician (NK) twice with an interval of 3 weeks.

Linear mixed effect models were fitted for responses. Within DRR and CT measurements, separate models were fitted for each measurement (MCS, TFO, and TFCS) and, for DRR measurements, within each view. Cadaver, a random effect, and foot (left or right), a fixed effect, were included in all models in addition to the variables presented. Models were fitted for subsets of the data and estimates and 95% CI were given for differences in measurements in different levels of a specific variable. For each of the models, only the differences in response that were associated with either different torques, or different conditions were calculated; the data was subset by the other two variables and they remained constant within each model. The first set of models compared the differences in response for 10 Nm with 0 Nm of torque applied with full weight-bearing load (condition constant within each model). The second set of models compared the differences in response between conditions 1 through 4 and the native ankles, with full weight-bearing load (torque constant within each model). Coefficients and 95% CIs were reported, and statistical significance (marked by an asterisk in all tables and graphs) was determined based on a p value of less than 0.05.

Pearson's correlation was used to assess the relationship between DRR—AP view only—and CT. Correlation was graded as very strong (>0.80), strong (0.60–0.80), moderate (0.40–0.60), weak (0.20–0.40), and very weak (<0.20). For each measurement, values were paired by cadaver, foot, condition, and torque, and the correlation estimated between the pairs was computed. Confidence intervals were constructed using the Fisher transformation. All calculations were performed in R 3.4.1, specifically using packages psych and lmerTest.

Results

Digitally reconstructed radiographs

The average internal rotation to reconstruct a mortise view out of an AP view was 9.9 ± 1.4º (range 8.0–13.9º). Inter- and intra-observer agreement for measurements made on DRRs were rated as very good/good for the MCS and TFO (Table 1). TFCS measurements were rated as moderate for inter- and very good (AP view)/good (mortise view) for intra-observer reliability. Torque had a significant impact on MCS measurements if any of the four ligaments was transected, but not on native ankles (Table 2). The TFCS significantly decreased for native ankles (AP and mortise view) and additionally for condition 1 (mortise view) if torque was applied. A significant increase in the TFCS was evident for condition 4 (mortise view, including torque). TFO measurements on native ankles and on each condition significantly decreased if torque was applied. The AITFL and deltoid ligament had to be transected to detect a significant difference in the MCS on the AP and mortise views compared with native ankles (including torque, Fig. 3). For the TFCS, only fully dissected ankles (condition 4) significantly differed from native ankles (both views, including torque). Using the mortise view, condition 3 additionally differed significantly from native ankles when the TFCS was measured (including torque, Fig. 4). For the TFO, isolated AITFL release significantly differed from native ankles if torque was applied (Fig. 5).

Weight-bearing CTs

Inter- and intra-observer agreement for CT measurements were very good for each assessed parameter (Table 1). Torque had a significant impact on MCS measurements in native ankles and under each condition (Table 2). The TFCS significantly decreased in native ankles, for condition 1 and for condition 2, when torque was applied. Torque application had a significant impact on TFO measurements of native ankles and under each tested condition. The AITFL and deltoid ligament had to be transected to detect a significant difference for the MCS compared with native ankles if torque was applied (Fig. 6). The TFCS was

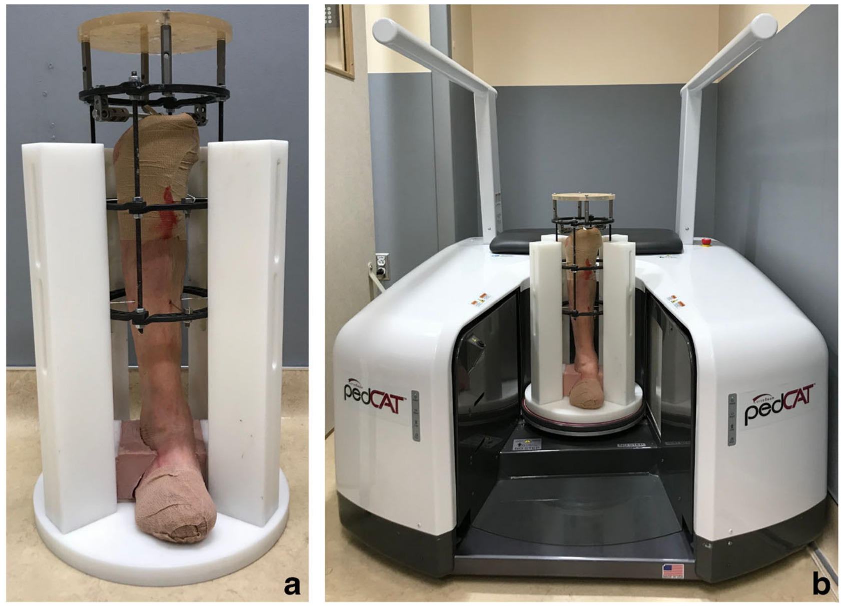

Fig. 1 Experimental setting. **a** Frame used to hold the cadaver in a plantigrade position. An Ilizarov apparatus was used for fixation of the tibia. **b** The frame fits into the weight-bearing CT apparatus. Load and torque can be applied following dissection of the distal tibio-fibular syndesmosis

helpful only in differentiating an intact from a disrupted syndesmosis after complete release of the AITF, deltoid ligament, and IOM (including torque application). Isolated AITFL transection was recognized by a significant change in TFO values when torque was applied. Correlation between DRR and CT measurements was best for the TFO (very strong), followed by the MCS (very strong) and TFCS (strong, Table 3).

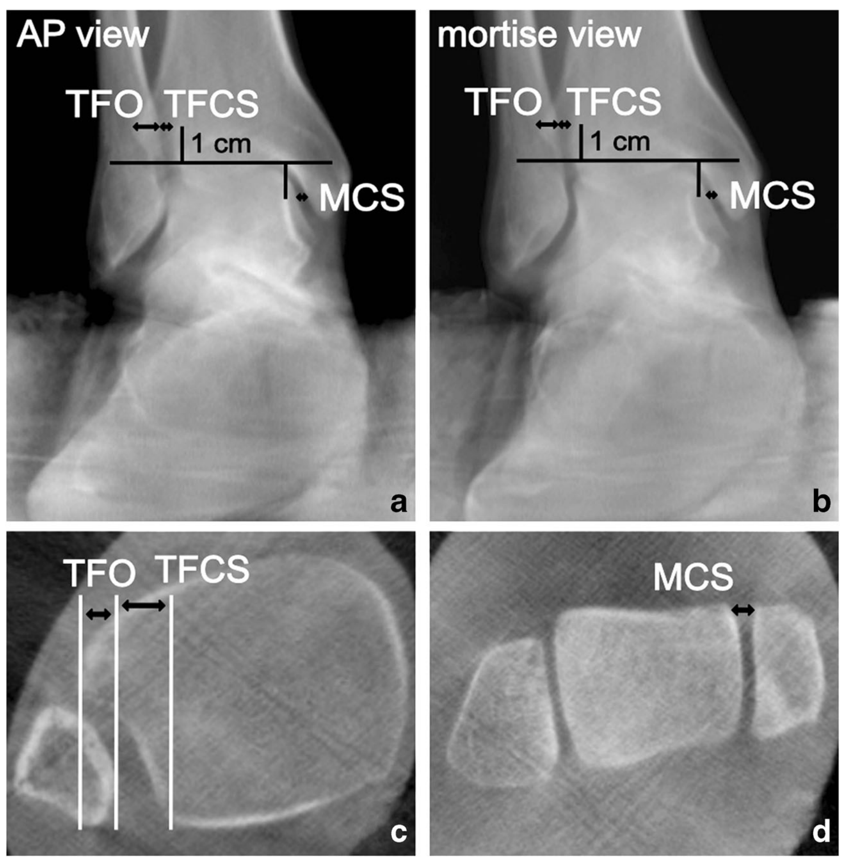

Fig. 2 Measurements performed using digitally reconstructed radiographs (DRRs) and single computed tomography (CT) images. **a** Antero-posterior (*AP*) view showing the medial clear space (*MCS*), tibio-fibular clear space (*TFCS*), and tibio-fibular overlap (*TFO*). **b** Mortise view of the same cadaver showing symmetrical widening of the ankle mortise. **c** Single CT image 1 cm above the ankle joint showing the TFCS and TFO. **d** Single CT image 1 cm below the ankle joint showing the MCS measured at the anterior-most part of the joint between the medial malleolus und the talus

Table 1 Reliability of DRR and computed tomography (CT) measurements assessed by intraclass coefficient (*ICC*)

		Inter-observer: ICC(2,1) Estimate (95% CI)	Intra-observer: ICC(3,1) Estimate (95% CI)
Antero-posterior digitally reconstructed radiograph	Medial clear space	0.75 (0.51, 0.87)	0.93 (0.87, 0.96)
	Tibio-fibular clear space	0.59[a] (0.35, 0.76)	0.88 (0.79, 0.94)
	Tibio-fibular overlap	0.95 (0.88, 0.98)	0.99 (0.97, 0.99)
Mortise digitally reconstructed radiograph	Medial clear space	0.87 (0.77, 0.93)	0.95 (0.91, 0.98)
	Tibio-fibular clear space	0.55[a] (0.29, 0.73)	0.70 (0.50, 0.83)
	Tibio-fibular overlap	0.92 (0.77, 0.97)	0.97 (0.94, 0.98)
Computed tomography	Medial clear space	0.94 (0.89, 0.97)	0.95 (0.92, 0.98)
	Tibio-fibular clear space	0.93 (0.74, 0.97)	0.94 (0.89, 0.97)
	Tibio-fibular overlap	0.92 (0.53, 0.98)	0.99 (0.97, 0.99)

CI Confidence interval

[a] Indicates ICC < 0.61

Table 2 Influence of torque application on measurements (weight-bearing): mean differences for each stage of dissection with and without torque application

			Estimate, mm (95% CI)				
			Native	Condition 1	Condition 2	Condition 3	Condition 4
Digitally reconstructed radiograph	Medial clear space	Antero-posterior	0.01 (−0.21, 0.23)	0.34 (0.08, 0.60)*	0.40 (0.02, 0.78)*	1.14 (0.39, 1.88)*	1.56 (1.02, 2.11)*
		Mortise	−0.07 (−0.33, 0.18)	0.50 (0.16, 0.83)*	0.92 (0.55, 1.28)*	1.62 (0.94, 2.29)*	1.90 (0.93, 2.87)*
	Tibio-fibular clear space	Antero-posterior	−0.77 (−1.22, −0.32)*	−0.44 (−0.75, −0.12)*	−0.29 (−0.81, 0.24)	0.14 (−0.69, 0.96)	0.31 (−0.54, 1.17)
		Mortise	−0.53 (−0.93, −0.13)*	0.17 (−0.41, 0.74)	0.29 (−0.30, 0.87)	0.48 (−0.45, 1.41)	1.43 (0.47, 2.38)*
	Tibio-fibular overlap	Antero-posterior	−2.89 (−3.60, −2.18)*	−3.38 (−4.50, −2.25)*	−3.92 (−4.69, −3.15)*	−4.63 (−5.54, −3.71)*	−3.93 (−5.42, −2.44)*
		Mortise	−2.44 (−3.15, −1.74)*	−2.96 (−3.88, −2.03)*	−3.12 (−3.92, −2.32)*	−2.64 (−3.39, −1.89)*	−2.50 (−3.45, −1.55)*
Computed tomography	Medial clear space		1.22 (0.62, 1.81)*	1.51 (1.18, 1.84)*	1.78 (1.27, 2.28)*	2.81 (1.37, 4.26)*	3.35 (1.77, 4.92)*
	Tibio-fibular clear space		−1.07 (−1.50, −0.65)*	−0.90 (−1.41, −0.40)*	−0.94 (−1.55, −0.33)*	−0.04 (−1.29, 1.20)	1.29 (−0.13, 2.71)
	Tibio-fibular overlap		−2.98 (−3.51, −2.45)*	−3.63 (−4.57, −2.69)*	−3.84 (−4.85, −2.82)*	−4.46 (−5.68, −3.24)*	−4.49 (−6.33, −2.65)*

*Indicates statistical significance ($p < 0.05$)

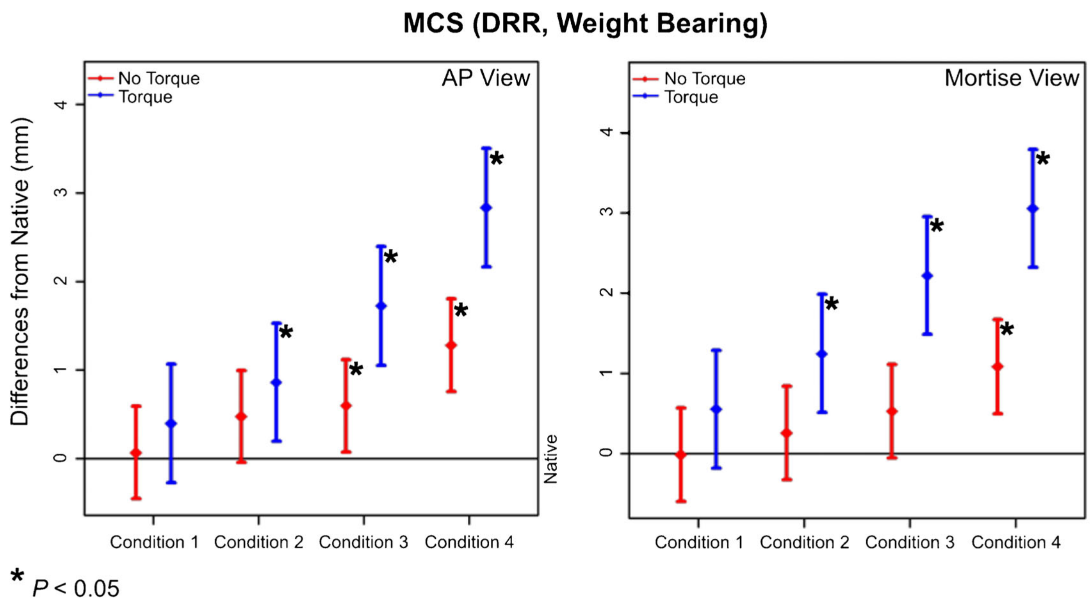

Fig. 3 Differences in the MCS between each tested condition and intact ankles (native) assessed on the AP and mortise views (DRRs). Using torque, the anterior–inferior tibio-fibular ligament (AITFL), in addition to the deltoid ligament, must be transected to detect a significant difference (AP and mortise views)

Discussion

A cadaver study examining the utility of weight-bearing CTs to assess incomplete and more complete syndesmotic injuries on DRRs and axial CT images was performed. The three most relevant findings were:

1. Torque application helps to identify incomplete syndesmotic injuries
2. The TFO was the most useful predictor for incomplete syndesmotic injuries
3. The MCS and TFCS predict more complete injuries

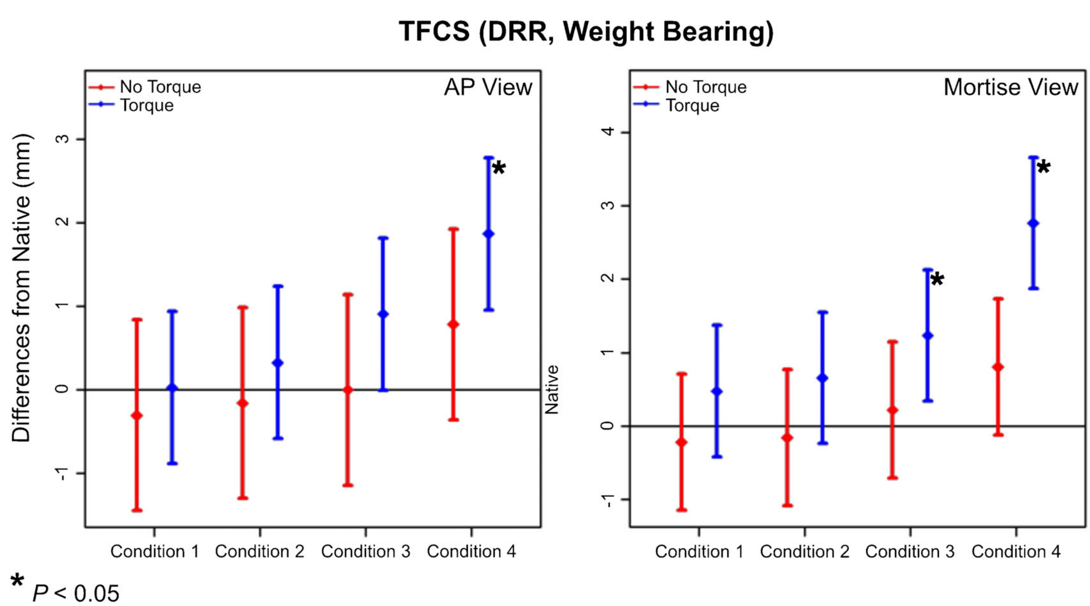

Fig. 4 Differences in the TFCS between each tested condition and intact ankles (native) assessed on the AP and mortise view (DRRs). Using torque, the AITFL, deltoid ligament, in addition to the interosseous membrane (IOM), must be transected to create a significant difference compared with intact ankles (mortise view)

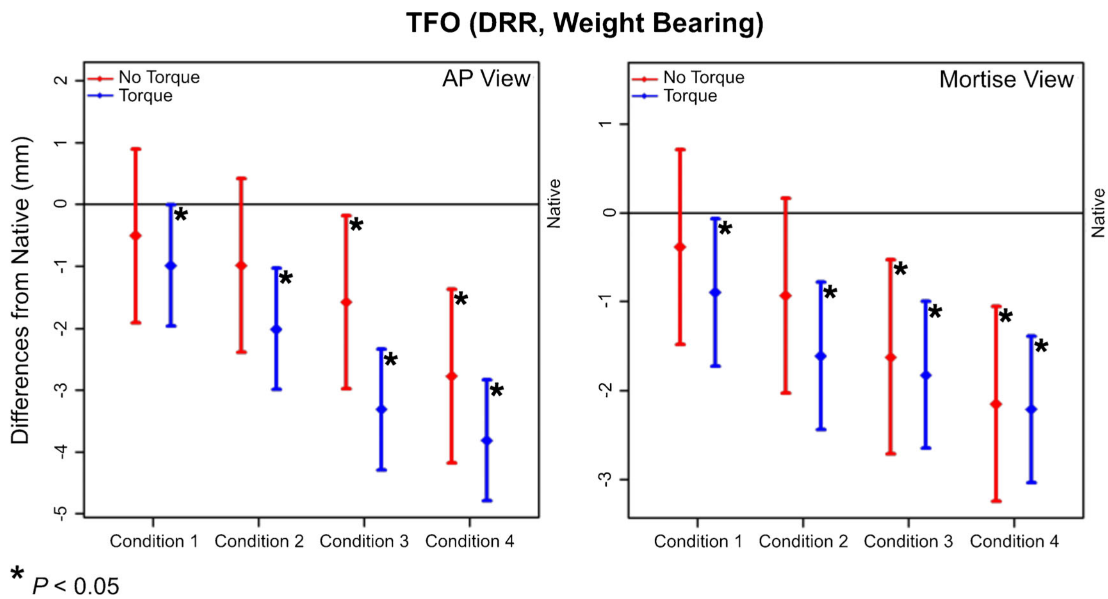

Fig. 5 Differences in the TFO between each tested condition and intact ankles (native) assessed on the AP and mortise views (DRRs). Isolated AITFL transection differed significantly from intact ankles on the AP and mortise views

The reliability of DRR measurements for MCS and TFO was comparable with published data for conventional radiographs [21, 25]. These two measurements can reliably be determined on conventional radiographs and DRRs. A similar result was evident for MCS and TFO measurements on axial CT images [23, 26]. The reliability for TFCS measurements on DRRs was slightly lower compared with published data for conventional radiographs [21]. The resolution of DRRs was also slightly lower than that of conventional radiographs, wherefore the identification of the antero-medial border of the distal tibial incisura was less precise on DRRs than on conventional radiographs, perhaps explaining the difference between the reliability of the TFCS measured on DRRs compared with published measurements on conventional radiographs [21]. However, TFCS measurements could reliably be performed on axial CT images. Consequently, the TFCS should be assessed on axial CTs rather than on DRRs.

The impact of torque on measurements describing the distal tibio-fibular syndesmosis has already been investigated in healthy volunteers, but the influence on measurement in patients with a syndesmotic injury is not yet fully understood [27]. Torque application helps to reveal incomplete syndesmotic injuries in this study. Without application of torque, only severe injuries could be identified. Recent research showed that measurements describing the distal tibio-fibular syndesmosis are highly dependent on the position of the ankle joint (e.g., rotation of the foot, dorsal-extension/plantar-flexion of the ankle joint) [28, 29]. A standardized position of the ankle when imaging is performed is therefore crucial for a meaningful interpretation of any measurements. Using weight-bearing CTs, torque can be applied with the foot in a plantigrade position (e.g., standing). This may be an advantage over other imaging modalities, where the rotation of the foot cannot be adjusted after imaging is performed (conventional radiograph), or the foot is in a nonweight-bearing condition (nonweight-bearing CT, MRI).

The TFO outperformed the other measurements to detect incomplete syndesmotic injuries. Including torque, single-ligament injuries (AITFL transection) could be differentiated from native ankles. This finding was independent of the imaging modality: both DRRs and single axial CT images showed the same result. This is different than recent research, where the TFO could not detect isolated AITF injuries when using stress fluoroscopy [30]. This result may be explained by the standardized setting used in this study: DRRs and axial CT images were reconstructed precisely to ensure no differences in rotation. MCS measurements were only useful in conditions where the deltoid ligament was additionally transected (DRRs and single CT images). Therefore, the MCS may be useful for identifying patients with an additional deltoid ligament injury. The TFCS, however, was only useful for predicting more complete syndesmotic injuries, including the posterior syndesmotic ligaments. Interestingly, torque decreased TFCS measurement except if the PITFL was dissected for most conditions. An intact PITFL may not allow the fibula to displace posteriorly if torque is applied. Therefore, TFCS

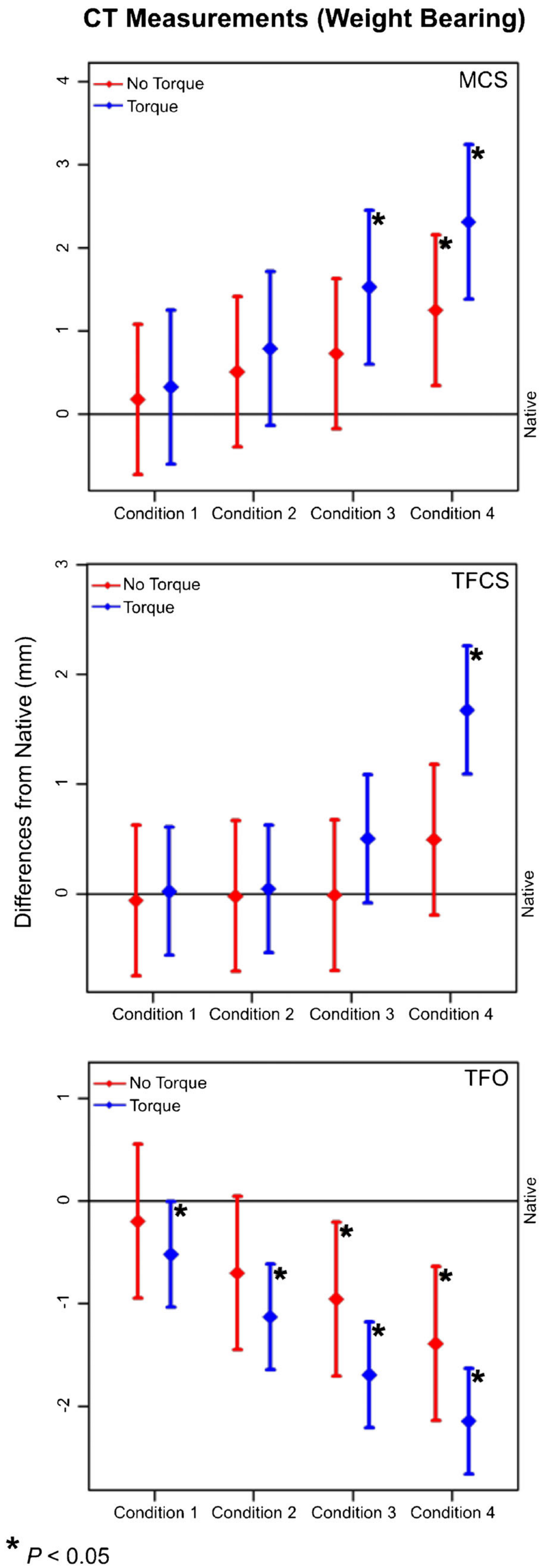

Fig. 6 Difference in the MCS, the TFCS, and the TFO between each tested condition and intact ankles (native) assessed on axial computed tomography (CT) images (weight-bearing condition). Results were similar to measurements carried out on DRRs. Using torque, the AITFL and deltoid ligament must be transected to create a significant difference in the MCS compared with intact ankles. For the TFCS, the IOM must be additionally transected, whereas for the TFO, isolated AITFL ligament transection significantly differed from intact ankles

measurements may be used to identify patients with an additional injury to the posterior part of the distal tibio-fibular syndesmosis.

Interestingly, the correlation between measurements carried out on DRRs and on axial CT images was very strong for the MCS and TFO, and strong for the TFCS. Given the fact that the reliability of measurements was comparable for DRRs and axial CT images when using the MCS and TFO, those two measurements can be assessed on either DRRs (weight-bearing) or axial CT images (weight-bearing). The TFCS, however, should only be assessed on axial CT images rather than on DRRs, as DRRs are less reliable.

Our study has several limitations. A cadaver model was used to assess the impact of torque on the assessment of syndesmotic injuries. In vivo, fixation of the calcaneus using K-wires is not feasible. The utility of applying torque to patients will require further experimentation and innovation. However, the amount of torque applied in this study (10 Nm) is relatively small and should be well tolerated. A second limitation is the precise transection of ligaments when using a cadaver model to mimic syndesmotic injuries. Under post-traumatic conditions, different ligaments of the distal talo-fibular syndesmosis are variably torn and healed. Such complex injuries cannot be simulated accurately using cadaver models. Finally, several different measurement options using either conventional radiographs or CTs are available. This study only investigated three commonly used measurements. Other measurements may be better predictors for injuries to the distal tibio-fibular syndesmosis.

To conclude, the application of torque helps when using weight-bearing CT images to identify incomplete syndesmotic injuries (cadaver model). The TFO is a better predictor for incomplete syndesmotic injuries, and the MCS and TFCS can be used for more complete lesions.

Table 3 Correlation between DRR (AP view) and CT measurements

Measurement	Estimate (95% CI)
Medial clear space	0.83 (0.78, 0.87)
Tibio-fibular clear space	0.80 (0.75, 0.85)
Tibio-fibular overlap	0.93 (0.91, 0.95)

Pearson's correlation with CIs computed using the Fisher transformation

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Compliance with ethical standards

Conflicts of interest For the remaining authors, no conflicts of interest were declared.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

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