Clinical Radiology 74 (2019) 571.e1–571.e8

Contents lists available at ScienceDirect

Clinical Radiology

journal homepage: www.clinicalradiologyonline.net

Tibiofibular syndesmosis in asymptomatic ankles: initial kinematic analysis using four-dimensional CT

A. Mousavian [a], D. Shakoor [b,*], N. Hafezi-Nejad [b], A. Haj-Mirzaian [b], C. de Cesar Netto [a], J. Orapin [a], L.C. Schon [a], S. Demehri [b]

[a] *Department of Orthopedic Surgery, MedStar Union Memorial Hospital, Baltimore, MD, USA*
[b] *Russell H. Morgan Department of Radiology and Radiological Sciences, Johns Hopkins University, Baltimore, MD, USA*

ARTICLE INFORMATION

Article history:
Received 26 October 2018
Accepted 19 March 2019

AIM: To evaluate the reliability of ankle syndesmotic measurements and their changes during active motion using four-dimensional computed tomography (4DCT) examination in asymptomatic ankles.

MATERIALS AND METHODS: 4DCT was performed on both ankles of patients with signs and symptoms of unilateral ankle instability. Ankles from the asymptomatic side of 10 consecutive patients were included in this analysis. Five ankle syndesmotic measurements were adopted from the available literature and performed by two fellowship-trained foot and ankle surgeons: (1) syndesmotic anterior distance (SAD); (2) syndesmotic posterior distance (SPD); (3) syndesmotic translation (ST); (4) syndesmotic tibiofibular angle (STFA); and (5) ankle tibiofibular angle (ATFA). A Monte Carlo simulation was also performed to obtain exact *p*-values with 99% confidence intervals.

RESULTS: Excellent interobserver reliability was observed among the two readers for four out of five measurements (intra-class correlation coefficients [ICC]: 0.767–0.995, $p<0.001$–0.020). The ICC values for SAD were not statistically significant (ICC=0.548 and 0.569 for dorsi and plantarflexion respectively, $p=0.1$). Among the five measurements, only ST measurements had significant changes during active motion (median [interquartile range] for change: −0.70 mm [−1.6–0.10]; $p=0.012$). Of the above measurements, only the ST measurements demonstrated a negative linear association with the tibiocalcaneal angle during active motion (beta=−2.5, $p=0.04$).

CONCLUSIONS: Reliable quantitative kinematic assessment of ankle syndesmosis can be performed using 4DCT examination. Syndesmotic measurements remain unchanged during ankle motion except for the syndesmotic translation, which tends to decrease during plantar flexion.

© 2019 Published by Elsevier Ltd on behalf of The Royal College of Radiologists.

* Guarantor and correspondent: D. Shakoor, Russell H. Morgan Department of Radiology and Radiological Sciences, Johns Hopkins University, 601 North Caroline Street, Baltimore, MD, USA. Tel.: +1 (443) 287 7503; fax: +1 (410) 502 6454.
E-mail address: delaramshakoor@mail.com (D. Shakoor).

https://doi.org/10.1016/j.crad.2019.03.015
0009-9260/© 2019 Published by Elsevier Ltd on behalf of The Royal College of Radiologists.

Introduction

The ankle syndesmotic ligament complex plays a pivotal role in maintaining the integrity of the distal tibiofibular joint and is frequently involved in sport-related injuries.[1–3] It is estimated that 5–10% of ankle sprains and 13–20% of ankle fractures are accompanied by syndesmotic injuries, although the true incidence is likely underestimated because of under-diagnosis in patients with subtle syndesmotic injuries.[1] Failure to diagnose syndesmotic injuries and late treatment could lead to long-term pain and instability, as well as development and accelerated progression of secondary osteoarthritis of the ankle.[1,4–6]

Several clinical examination techniques, including the squeeze test,[7] cotton test,[8] fibular translation test,[9] and tap test have been described and implemented in clinical practice; however, none has shown high accuracy for detecting syndesmotic injuries.[2,7,10–12] Furthermore, standard radiographic measures, such as medial clear space, anteroposterior tibiofibular clear space, and tibiofibular overlap, have failed to accurately assess syndesmotic injuries.[2,10,11,13] Considering the clinical importance of syndesmotic injuries and the lack of clinical and radiographic measures to accurately evaluate the distal tibiofibular joint, the use of advanced imaging techniques with high-resolution capabilities, such as computed tomography (CT) and magnetic resonance imaging (MRI), has received considerable attention in routine clinical practice.[14] Several recent studies have detailed the normal anatomy of the ankle syndesmosis, as well as novel measures and techniques to detect syndesmotic injuries using CT and MRI.[15–21] These conventional static CT and MRI examinations improve detection of syndesmotic injury by providing detailed osseous and soft-tissue resolution, respectively; however, they fail to detect and characterise biomechanical abnormalities and the resultant biomechanical instability associated with syndesmotic injuries.

Four-dimensional CT (4DCT) is a feasible, non-invasive imaging method that provides a kinematic evaluation of peripheral joints, including the hip,[22,23] knee,[24,25] elbow,[26,27] and wrist,[28–30] during active motion with high temporal resolution. Because of the ability of 4DCT to capture ankle motion using high-resolution three-dimensional imaging, this technique can potentially detect subtle instability related to syndesmotic injuries in patients who have inconclusive findings on conventional static CT or MRI examination.

The present study describes and evaluates the reliability and reproducibility of syndesmotic measurements (derived from previous CT or radiographic indices) using predefined anatomical landmarks in planes derived from double-oblique multiplanar reformation (MPR). These measurements were obtained during asymptomatic ankle dorsiflexion–plantar flexion motion using 4DCT images. The effect of foot position on the syndesmotic measurements was determined and change during active motion in asymptomatic ankles was assessed using 4DCT examination.

Materials and methods

All aspects of this study were performed following the Health Insurance Portability and Accountability Act, and institutional review board approval was obtained.

Study participants

The 4DCT examinations were performed for 12 participants with unilateral ankle pain and/or instability from October 2014 to December 2017. Informed consent was obtained from all participants before image acquisition. All participants were examined by two board-certified foot and ankle surgeons and were referred to the radiology department for 4DCT examination. Participants were instructed to perform active range of motion of both ankles, from maximal dorsiflexion to maximal plantar flexion, to the best of their ability. The 4DCT examinations were obtained during active range of motion of both ankles (symptomatic and asymptomatic sides). Asymptomatic contralateral ankles were scanned primarily to aid detection of subtle biomechanical instabilities on the symptomatic side and were confirmed by the referring orthopaedic surgeon to have no abnormality during physical examination. From the scanned asymptomatic contralateral ankles, only those with no evidence of abnormality (including hindfoot osteoarthritis) on static CT examination were included. Therefore, 10 ankles met the inclusion criteria and were analysed in this study.

Imaging protocol

Four-dimensional CT was performed using a 320-row-detector CT machine (Aquilion ONE; Toshiba, Tokyo, Japan) with an adaptive iterative dose-reduction construction algorithm. The current and tube potential were set at 100 mAs and 100 kV, respectively. The field of view of 4DCT acquisition included up to 16 cm of the distal third of the tibia to the midtarsal bones. During active motion, 10 consecutive CT scan volumes were obtained for each ankle (3–7 seconds; temporal resolution: 0.5 seconds). The position of the syndesmosis was documented with a post-processing protocol using predefined anatomical landmarks to improve the reliability of measurements between readers. Two board-certified, fellowship-trained foot and ankle surgeons performed syndesmotic measurements using Vitrea postprocessing software (Vital Images, Toshiba Medical Systems Company, Minnetonka, MN, USA). The measurements were performed during active motion from complete plantar flexion to dorsiflexion, in the bone window using thin sections (0.6 mm). The double-oblique MPR technique was used to define the plane of choice according to predefined anatomical landmarks. The reliability of the MPR method has been established for the evaluation of other peripheral joints.[28,29,31] To predefine the axial plane of choice in the reformatted coronal and sagittal planes, the cursor was placed in the centre of the ankle joint ensuring that the axial line was parallel to the tibial side of the ankle

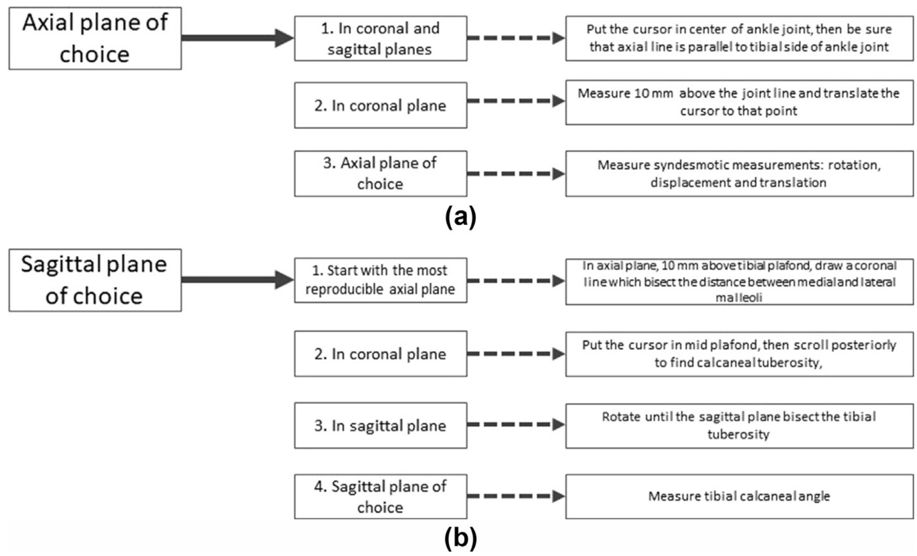

Figure 1 Predefined protocol for finding the best reformatted plane for sagittal and coronal measurements.

joint. Then, in the coronal plane, 10 mm above the joint line was measured and the cursor was translated to that point. The reformatted axial plane, which was determined as exactly 10 mm above the tibial plafond, was the plane of choice for performing syndesmotic measurements (Figs 1 and 2).

4DCT measurements

Five measurements were performed, including two angles and three measurements of distance. First, using the reformatted axial plane, a line connecting the anterior and posterior tibial tubercles of the fibularis incisura was drawn. Anterior and posterior intersections of the tibia with the mentioned line were defined as points A and B, respectively. The fibular axis was then drawn and the most anterior and posterior points on the fibula defined as points C and D, respectively. Two measurements assessing diastasis between the tibia and fibula were undertaken. The syndesmotic anterior distance was obtained by measuring the distance between points A and C (Fig 3).[10,18] The syndesmotic posterior distance was determined by measuring the distance between points B and D (Fig 3).[10,18] For evaluation of the anteroposterior displacement of the fibula, a line tangential to the anterolateral surface of the fibula was drawn and the distance between the anterior margins of the tibia with this line measured. This measurement was defined as syndesmotic translation, and a negative measurement indicated posterior translation of the fibula in relation to the tibia (Fig 4).[32]

Angle measurements

The syndesmosis tibiofibular angle was also created by the intersection of the fibular axis and the line connecting the anterior and posterior tibial tubercles (Fig 5).[33] The tibiofibular angle was calculated at two planes: at the level of syndesmosis, which is the predefined axial plane, and at the level of the ankle, which is at the most distal part of tibial plafond.

During the above syndesmotic measurements, the corresponding dorsiflexion–plantar flexion angles of the ankle were also recorded using the tibiocalcaneal angle (TCA) at the sagittal plane exactly parallel to the tibial axis (Fig 1).

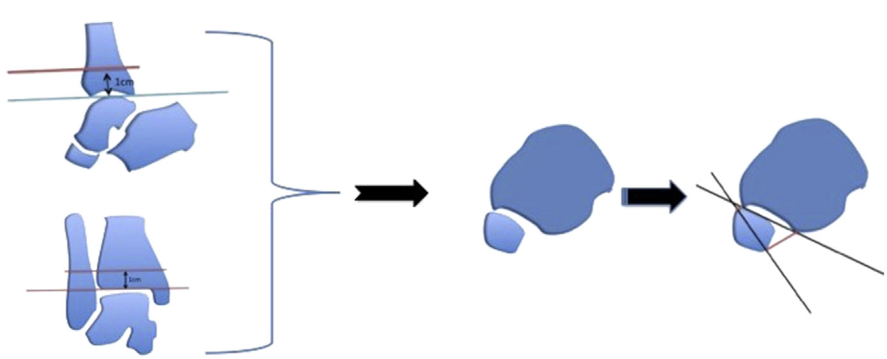

Figure 2 Illustration of the plane of choice for axial syndesmotic measurements and specific protocol for SAD and SPD as well as TFA using specific reproducible points.

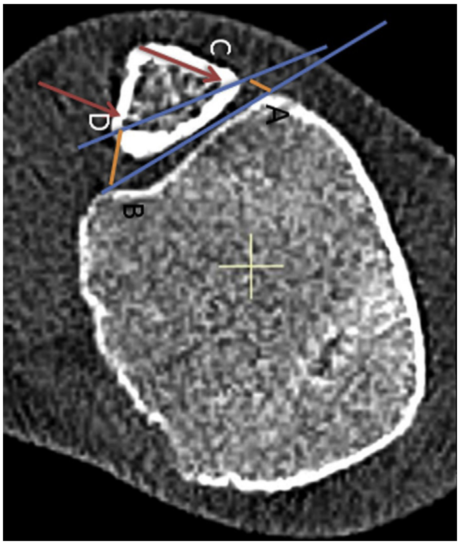

Figure 3 Illustration of exact reference points in the axial plane. SAD, distance between point A to C; SPD, distance between point B to D measurement methods.

First, a vertical line through three midpoints of the tibia was drawn. Then, a second line was drawn connecting the apex of the angle of Gissane and the posterior body of the calcaneus. TCA was defined as the angle between these two lines.[34]

Statistical analysis

Measurements were recorded, and the Shapiro–Wilk test was used to assess the normality of measurement distribution. Because the distribution of data was not normal, data are presented as medians and interquartile ranges (IQRs). The measurements were evaluated in three models: static dorsiflexion, static plantar flexion, and change from dorsiflexion to plantarflexion. Interclass correlation coefficients (ICCs) were used to assess interobserver consistency and agreement. A correlation of 0.75–1 was considered excellent, 0.61–0.74 was considered good, 0.4–0.60 was considered fair, and $<$0.4 was considered poor.[35,36] Measurements were obtained in the two extreme ends the range of motion (dorsiflexion and plantar flexion) and were compared using the Wilcoxon rank test for dependent samples.[37] Bootstrapping with 10,000 samples was used to extract p-values for 99% uncertainty levels. Next, the above five measurements were evaluated as functions of the TCA. Linear regression models were built, and the standardised beta values were extracted. The analysis was performed using PASW, version 18, software (SPSS, Chicago, IL, USA) and R platform, version 2.15.1 (R Foundation for Statistical Computing, Vienna, Austria).

Results

Study participants were nine women and one man (three right ankles and seven left ankles) with a mean age of 47.4 (range, 18 to 63) years and a mean body mass index of 29.8 (range, 20.9 to 39.7). Good to excellent ICCs were observed for consistency and absolute agreement among two readers in four of five measures (syndesmotic posterior distance, syndesmotic translation, tibiofibular angle at the level of syndesmosis, and tibiofibular angle at the level of ankle, but not syndesmotic anterior distance; Table 1). For consistency, the ICC range was 0.767–0.995 ($p<0.05$). For absolute agreement, the ICC range was 0.777–0.994 ($p<0.05$). Regarding ICC values for syndesmotic anterior distance, good to excellent correlation was observed in the plantar flexion model ($p=0.02$); however, the ICC values were not significant in the dorsiflexion model ($p=0.12$; Table 1).

Table 2 presents the median of 4DCT ankle syndesmotic measurements, along with changes in ankle syndesmotic measurements between the extreme ends of ankle range of motion. Among five measurements, only syndesmotic translation values changed significantly during active movement (median [IQR] for change: −0.70 mm [−1.6 to −0.10]; $p=0.012$). A Monte Carlo simulation was performed to confirm the observed effect and to obtain exact p-values with 99% confidence intervals ($p=0.007$).

The possible association between syndesmotic measurements and active ankle motion was also evaluated (TCA; Table 3 and Fig 6). A negative linear association was

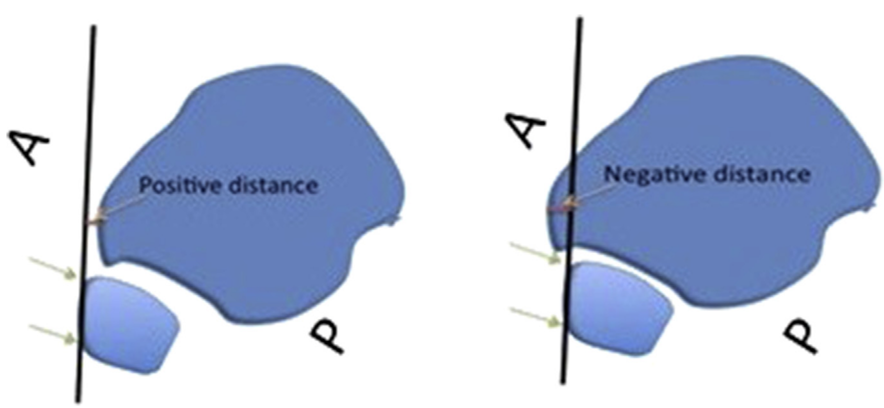

Figure 4 Illustration of ST and its positive (as indicated by posterior position of tibia relative to the tangential line to anterolateral surface of fibula) and negative values (as indicated by anterior position of tibia relative to the tangential line to anterolateral surface of fibula).

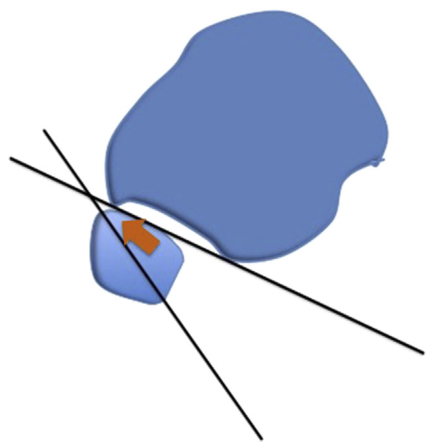

Figure 5 Depiction of STA.

Table 1
Interobserver reliability of syndesmosis measurements at the extreme ends of motion.

Index	ICC for consistency		ICC for absolute agreement	
Measurement	Dorsiflexion	Plantar flexion	Dorsiflexion	Plantar flexion
1. Syndesmotic anterior distance (SAD)	0.548 p=0.126	0.750 p=0.026	0.569 p=0.126	0.742 p=0.026
2. Syndesmotic posterior distance (SPD)	0.896 p=0.001	0.858 p=0.004	0.905 p=0.001	0.867 p=0.004
3. Syndesmotic translation (ST)	0.767 p=0.020	0.995 p<0.001	0.777 p=0.020	0.994 p<0.001
4. Syndesmotic tibiofibular angle (STFA)	0.977 p<0.001	0.975 p<0.001	0.975 p<0.001	0.977 p<0.001
5. Ankle tibiofibular angle (ATFA)	0.974 p<0.001	0.801 p=0.012	0.968 p<0.001	0.817 p=0.012

ICC, intraclass correlation coefficients.

observed between syndesmotic translation values and TCA in active motion (standardised beta: −2.5; p=0.04); however, the relationships between other measurements and TCA were not significant.

Discussion

Syndesmotic injuries precipitate diastasis between the distal tibia and fibula, which creates biomechanical instability in the ankle.[38,39] During ambulation, the axial forces on the tibiotalar joint can reach up to four times the body weight, so even minor incongruence can have a major effect on the ankle, particularly during active motion.[14] Therefore, restoration of the normal anatomy of the ankle and its injured syndesmosis is critical to avoid chronic instability and associated post-traumatic osteoarthritis; however, the metrics to confirm successful surgical correction have been a matter of debate.[11,15,40] Studies have emphasised the superiority of conventional static CT images in detecting minor syndesmotic injuries; however, there is conflicting evidence regarding the accuracy and precision of the described measurements in identifying syndesmotic injuries.[13,41,42] Various factors could be responsible for such discrepancies. Most studies of syndesmotic measurements were performed in patients with previous injury or in cadavers,[18,19,43,44] and few studies were performed in healthy patients.[10,15,20,33] Different anatomical landmarks have been used to determine syndesmotic measurements, producing conflicting results because of the wide variability in the shape, depth, and configuration of the fibularis incisura. It has also been reported that ankle motion can affect the position of the fibula relative to the incisura; however, no study to the authors' knowledge has evaluated the change in fibular position during active motion.[14,33]

In the present study, a novel 4DCT examination was used to evaluate syndesmotic measurements during active motion of the ankle. The results indicate that selected syndesmotic measurements during active motion of the ankle offer excellent reproducibility and reliability. Additionally, all syndesmotic measurements except syndesmotic translation were unchanged during active motion; therefore, their changes during dorsiflexion–plantar flexion in symptomatic ankles could represent associated syndesmosis-related instability.

Compared with previous studies, the present study achieved a higher level of reliability in syndesmotic measurements (ICC range=0.548–0.995).[18] This observation could be the result of a combination of predefined measurement protocols used in this study. First, reformatted axial plane of choice was set for axial measurement 10 mm above the tibial plafond using double-oblique MPR. This technique enabled the plane exactly parallel to the tibial plafond to be chosen; thus, the plane of choice was set at exactly the same level throughout ankle motion, which is critical for obtaining consistent data. Furthermore, previous studies reported vague descriptions of their reference

Table 2
4DCT measurements of Distal tibiofibular syndesmosis during dorsi-flexion to plantar flexion motion.

Measurements	Dorsiflexion Median (IQR)	Plantar flexion Median (IQR)	Change Median (IQR)	p-Value	Monte Carlo simulation; p-value
1. Syndesmotic anterior distance (SAD), mm	3.6 (3.3–4.8)	3.5 (2.8–4.3)	−0.6 (−1–0.1)	0.050	0.061
2. Syndesmotic posterior distance (SPD), mm	7.6 (5.6–9.8)	6 (5.4–9)	0.00 (−1.9–0.6)	0.327	0.377
3. Syndesmotic translation (ST), mm	2.6 (1–3.1)	1.8 (−0.2–2.4)	−0.70 (−1.6–−0.10)	0.012	0.007
4. Syndesmotic tibiofibular angle (STFA), degrees	−12.27 (−16.35–−6.34)	−11.74 (−15.60–−6.30)	−0.36 (−2.37–2.72)	0.878	0.922
5. Ankle tibiofibular angle (ATFA), degrees	4.11 (1.00–8.62)	3.80 (1.26–9.54)	0.65 (−1.45–2.32)	0.678	0.739

Changes in syndesmotic measurements in the extreme ends of motion are also displayed. Monte Carlo simulation with 10,000 samples were used to extract p-values for 99% uncertainty levels.
IQR, interquartile range.

Table 3
Linear association between active motion (tibiocalcaneal angle) and syndesmotic measurements.

Measurement	Original data		After bootstrapping	
	Standardised beta	*p*-Value	Standardised beta	*p*-Value
1. Syndesmotic anterior distance (SAD)	−0.72	0.551	−0.72	0.534
2. Syndesmotic posterior distance (SPD)	0.05	0.966	0.05	0.969
3. Syndesmotic translation (ST)	−2.50	0.040	−2.50	0.025
4. Syndesmotic tibiofibular angle (STFA)	0.47	0.696	0.47	0.678
5. Ankle tibiofibular angle (ATFA)	1.79	0.147	1.79	0.149

Bootstrapping was performed based on 10,000 bootstrap samples (99% uncertainty levels).

points, which made their results less reliable.[10,11,15,33] This ambiguity in reference point determination could also lead to measurement error in the region of the ankle joint, which is known for high variability in anatomical osseous structure. In the present study, determination of a consistent set of reference points using the anterior and posterior tubercles and fibular axis ensured high measurement reliability.

A negative linear association was observed between the syndesmotic translation and TCA during active motion. Previous studies also have reported translation of the fibula relative to the tibia during ankle external/internal rotation.[17,45] This translation may likely be explained by the wedge shape of the talus, which has a wider anterior portion than the posterior portion.[46] Previous studies of kinematics of normal ankles have shown that the fibula rotates externally and displaces laterally to enable the mortise to accommodate the wider anterior aspect of the talus.[47] During plantarflexion–dorsiflexion, the fibula slides forward to accommodate the wide anterior aspect of talus

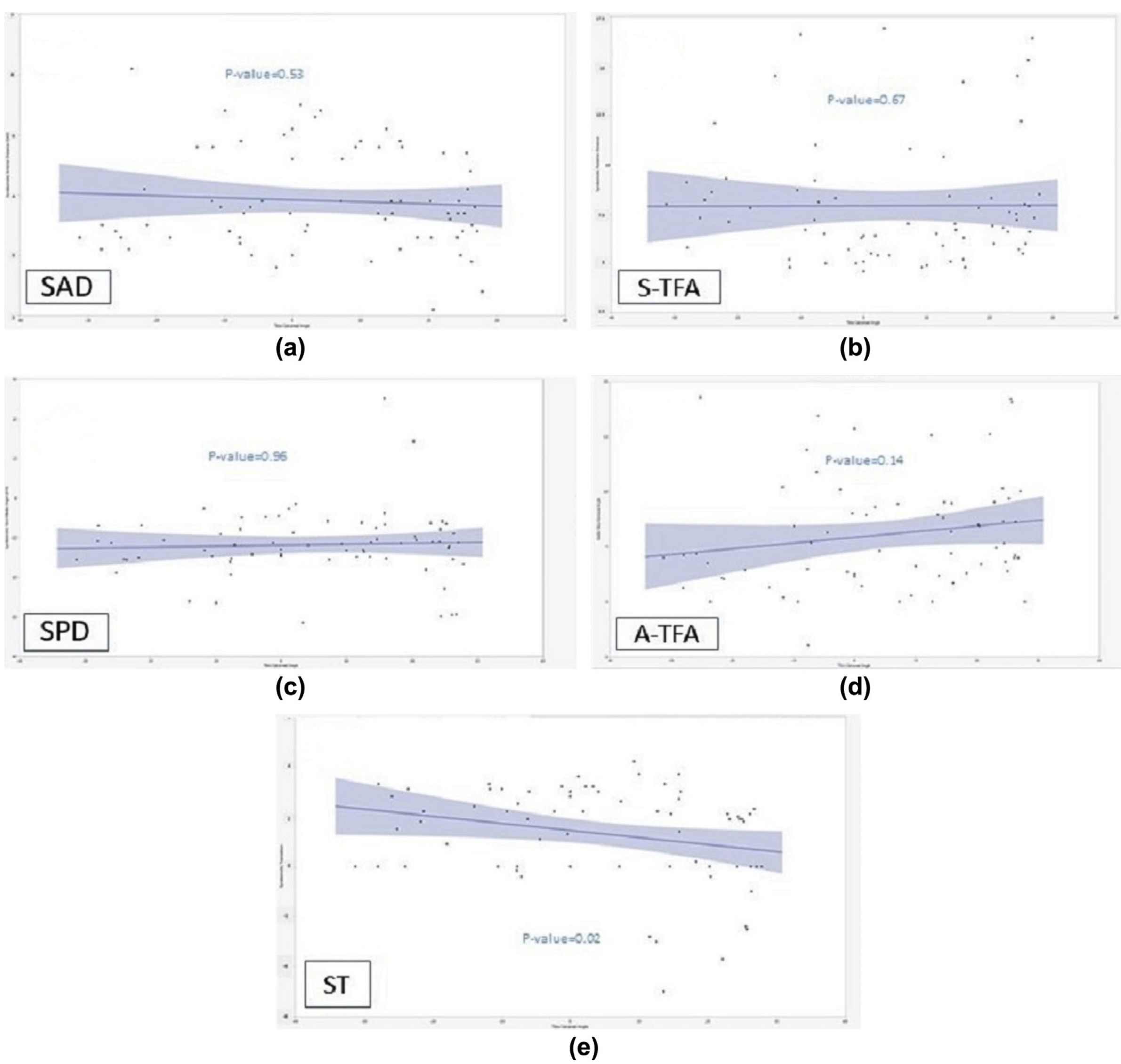

Figure 6 Linear association between sagittal ankle motion and syndesmotic measurements. (a) Association between tibiocalcaneal angle and SAD. (b) Association between tibiocalcaneal angle and S-TFA. (c) Association between tibiocalcaneal angle and SPD. (d) Association between tibiocalcaneal angle and A-TFA. (e) Association between tibiocalcaneal angle and ST.

in the mortise; however, no significant changes were observed in diastasis or rotation measurements during motion. This could be attributed to the fact that the measurements were performed on an axial plane, 10 mm above the tibial plafond, and fibular displacement and rotation could be higher on more distal planes, such as ankle level or 5 mm below the talar dome. A previous study also reported no significant change in syndesmotic tibiofibular angle during ankle external/internal rotation on the same plane as ours. In addition, there are no data regarding whether these measurements have sufficient accuracy to detect fibular displacement; thus, further studies are required to address this matter robustly.

The present findings suggest that fibular translation normally occurs during ankle motion, as evidenced by the significant change in syndesmotic translation. This is in contrast with a previous study that reported that the fibula is normally located anteriorly or centrally to the incisura, in which the authors suggested that posterior translation of the fibula could be a sign of malreduction in patients with previous ankle surgery.[45] Although the authors reported the imaging findings of 104 healthy ankles, they did not mention whether these ankles were in a neutral position during imaging and did not report the degree of dorsal or plantar flexion of the ankles during imaging. Thus, based on the present findings of fibular translation, the degree of ankle flexion during imaging should be considered, because the fibula translates during motion.

The present study has several limitations. First, no definitive diagnostic tools were available to confirm that any syndesmotic instability was present, and this could have biased our results. Second, the asymptomatic ankles of patients referred to the centre were used. Although only asymptomatic ankles with normal physical examinations and static CT examinations were included, subtle soft-tissue and ligamentous injuries (detectable only by MRI) that could not be detected clinically and may have been missed on imaging. Third, previous studies have shown that some measurements might differ between men and women; however, the results could not be stratified based on participant sex because the collection of asymptomatic ankles consisted of nine female participants and only one male participant. Fourth, in the current literature several measurements have been described for the assessment of syndesmotic injuries, and it is unfeasible to implement all measurements in one study; thus, the most cited and reliable measures were selected for the study. Further investigation is required to evaluate other measures using the 4DCT technique. Lastly, because the 4DCT technique has been implemented only recently, the sample size was small and the study may be underpowered to detect significant in for syndesmotic measurements during ankle motion; thus, further studies with larger sample sizes are warranted.

In conclusion, reliable evaluation of ankle syndesmosis can be performed using 4DCT examination. Syndesmotic measurements are independent of ankle motion except for the amount of syndesmotic translation, which tends to decrease during plantar flexion.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

C.d.C.d.N. is a paid consultant and shareholder of CurveBeam and a consultant to Ossio. L.C.S. received research grants from Zimmer, Wright Medical, Smith and Nephew, Spine-Smith/Celing Bioscience, Carestream Health, and received research support from Arthrex, DJO, and DAR. S.D. received research support from General Electric and Carestream Health, and is also a consultant for Toshiba.

References

1. Fort NM, Aiyer AA, Kaplan JR, *et al.* Management of acute injuries of the tibiofibular syndesmosis. *Eur J Orthop Surg Traumatol* 2017;**27**(4):449–59.
2. Del Buono A, Florio A, Boccanera MS, *et al.* Syndesmosis injuries of the ankle. *Curr Rev Musculoskel Med* 2013;**6**(4):313–9.
3. Hermans JJ, Beumer A, de Jong TA, *et al.* Anatomy of the distal tibiofibular syndesmosis in adults: a pictorial essay with a multimodality approach. *J Anat* 2010;**217**(6):633–45.
4. Sagi HC, Shah AR, Sanders RW. The functional consequence of syndesmotic joint malreduction at a minimum 2-year follow-up. *J Orthop Trauma* 2012;**26**(7):439–43.
5. Zalavras C, Thordarson D. Ankle syndesmotic injury. *J Am Acad Orthop Surg* 2007;**15**(6):330–9.
6. Kortekangas T, Flinkkila T, Niinimaki J, *et al.* Effect of syndesmosis injury in SER IV (Weber B)-type ankle fractures on function and incidence of osteoarthritis. *Foot Ankle Int* 2015;**36**(2):180–7.
7. Sman AD, Hiller CE, Rae K, *et al.* Diagnostic accuracy of clinical tests for ankle syndesmosis injury. *Br J Sports Med* 2015;**49**(5):323–9.
8. Beumer A, Swierstra BA, Mulder PG. Clinical diagnosis of syndesmotic ankle instability: evaluation of stress tests behind the curtains. *Acta Orthop Scand* 2002;**73**(6):667–9.
9. Ogilvie-Harris DJ, Reed SC. Disruption of the ankle syndesmosis: diagnosis and treatment by arthroscopic surgery. *Arthroscopy* 1994;**10**(5):561–8.
10. Elgafy H, Semaan HB, Blessinger B, *et al.* Computed tomography of normal distal tibiofibular syndesmosis. *skeletal Radiol* 2010;**39**(6):559–64.
11. Ahn TK, Choi SM, Kim JY, *et al.* Isolated syndesmosis diastasis: computed tomography scan assessment with arthroscopic correlation. *Arthroscopy* 2017;**33**(4):828–34.
12. de Cesar Netto C, Pinto M, Roberts L, *et al.* Intraoperative tap test for coronal syndesmotic instability: a cadaveric study. *Injury* 2018.
13. Ebraheim NA, Lu J, Yang H, *et al.* Radiographic and CT evaluation of tibiofibular syndesmotic diastasis: a cadaver study. *Foot Ankle Int* 1997;**18**(11):693–8.
14. Ebinger T, Goetz J, Dolan L, *et al.* 3D model analysis of existing CT syndesmosis measurements. *Iowa Orthop J* 2013;**33**:40–6.
15. Nault ML, Hebert-Davies J, Laflamme GY, *et al.* CT scan assessment of the syndesmosis: a new reproducible method. *J Orthop Trauma* 2013;**27**(11):638–41.
16. Nault ML, Marien M, Hebert-Davies J, *et al.* MRI quantification of the impact of ankle position on syndesmosis anatomy. *Foot Ankle Int* 2017;**38**(2):215–9.
17. Lepojarvi S, Niinimaki J, Pakarinen H, *et al.* Rotational dynamics of the normal distal tibiofibular joint with weight-bearing computed tomography. *Foot Ankle Int* 2016;**37**(6):627–35.
18. Davidovitch RI, Weil Y, Karia R, *et al.* Intraoperative syndesmotic reduction: three-dimensional versus standard fluoroscopic imaging. *J Bone Joint Surg [Am]* 2013;**95**(20):1838–43.

19. Phisitkul P, Ebinger T, Goetz J, *et al*. Forceps reduction of the syndesmosis in rotational ankle fractures: a cadaveric study. *J Bone Joint Surg [Am]* 2012;**94**(24):2256–61.
20. Tang CW, Roidis N, Vaishnav S, *et al*. Position of the distal fibular fragment in pronation and supination ankle fractures: a CT evaluation. *Foot Ankle Int* 2003;**24**(7):561–6.
21. Vasarhelyi A, Lubitz J, Gierer P, *et al*. Detection of fibular torsional deformities after surgery for ankle fractures with a novel CT method. *Foot Ankle Int* 2006;**27**(12):1115–21.
22. Fernquest S, Arnold C, Palmer A, *et al*. Osseous impingement occurs early in flexion in cam-type femoroacetabular impingement: a 4D CT model. *Bone Joint J* 2017;**99-b**(Suppl. B):41–8.
23. Kishida S, Funabashi N, Harada Y, *et al*. Utility of four-dimensional analysis of the acetabular labrum applying motion-gated multislice computed tomography: comparison with arthroscopy and harris hip score. *J Comput Assist Tomogr* 2006;**30**(6):991–1000.
24. Demehri S, Thawait GK, Williams AA, *et al*. Imaging characteristics of contralateral asymptomatic patellofemoral joints in patients with unilateral instability. *Radiology* 2014;**273**(3):821–30.
25. Demehri S, Hafezi-Nejad N, Carrino JA. Conventional and novel imaging modalities in osteoarthritis: current state of the evidence. *Curr Opin Rheumatol* 2015;**27**(3):295–303.
26. Goh YP, Lau KK. Using the 320-multidetector computed tomography scanner for four-dimensional functional assessment of the elbow joint. *Am J Orthop (Belle Mead, NJ)* 2012;**41**(2):E20–4.
27. Yamamoto M, Murakami Y, Iwatsuki K, *et al*. Feasibility of four-dimensional preoperative simulation for elbow debridement arthroplasty. *BMC Musculoskel Disord* 2016;**17**:144.
28. Demehri S, Hafezi-Nejad N, Morelli JN, *et al*. Scapholunate kinematics of asymptomatic wrists in comparison with symptomatic contralateral wrists using four-dimensional CT examinations: initial clinical experience. *Skeletal Radiol* 2016;**45**(4):437–46.
29. Demehri S, Hafezi-Nejad N, Thakur U, *et al*. Evaluation of pisotriquetral motion pattern using four-dimensional CT: initial clinical experience in asymptomatic wrists. *Clin Radiol* 2015;**70**(12):1362–9.
30. Shores JT, Demehri S, Chhabra A. Kinematic "4 dimensional" CT imaging in the assessment of wrist biomechanics before and after surgical repair. *Eplasty* 2013;**13**.
31. Yin X, Xu R, Wang Y, *et al*. Implication of coronary CT angiography combined with four-dimensional speckle tracking echocardiography for predicting major adverse cardiac events. *Int J Cardiovasc Imaging* 2018;**34**(8):1287–93.
32. Reb CW, Hyer CF, Collins CL, *et al*. Clinical adaptation of the "tibiofibular line" for intraoperative evaluation of open syndesmosis reduction accuracy: a cadaveric study. *Foot Ankle Int* 2016;**37**(11):1243–8.
33. Dikos GD, Heisler J, Choplin RH, *et al*. Normal tibiofibular relationships at the syndesmosis on axial CT imaging. *J Orthop Trauma* 2012;**26**(7):433–8.
34. Arangio GA, Wasser T, Rogman A. The use of standing lateral tibial–calcaneal angle as a quantitative measurement of Achilles tendon contracture in adult acquired flatfoot. *Foot Ankle Int* 2006;**27**(9):685–8.
35. Fleiss JC JL. The equivalence of weighted kappa and the intraclass correlation coefficient as measures of reliability. *Educ Psychol Meas* 1973;**33**:613–9.
36. Fleiss JL. *Statistical methods for rates and proportions*. New York, NY: Wiley, John and Sons, Inc.; 1981.
37. Cicchetti DV. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. *Psychol Assess* 1994;**6**(4):284.
38. Vosseller JT, Karl JW, GreisberG JK. Incidence of syndesmotic injury. *Orthopedics* 2014;**37**(3):e226–9.
39. Gerber JP, Williams GN, Scoville CR, *et al*. Persistent disability associated with ankle sprains: a prospective examination of an athletic population. *Foot Ankle Int* 1998;**19**(10):653–60.
40. Malhotra G, Cameron J, Toolan BC. Diagnosing chronic diastasis of the syndesmosis: a novel measurement using computed tomography. *Foot Ankle Int* 2014;**35**(5):483–8.
41. Chen Y, Qiang M, Zhang K, *et al*. A reliable radiographic measurement for evaluation of normal distal tibiofibular syndesmosis: a multi-detector computed tomography study in adults. *J Foot Ankle Res* 2015;**8**:32.
42. Knops SP, Kohn MA, Hansen EN, *et al*. Rotational malreduction of the syndesmosis: reliability and accuracy of computed tomography measurement methods. *Foot Ankle Int* 2013;**34**(10):1403–10.
43. Gardner MJ, Demetrakopoulos D, Briggs SM, *et al*. Malreduction of the tibiofibular syndesmosis in ankle fractures. *Foot Ankle Int* 2006;**27**(10):788–92.
44. Krahenbuhl N, Weinberg MW, Davidson NP, *et al*. Imaging in syndesmotic injury: a systematic literature review. *skeletal Radiol* 2018;**47**(5):631–48.
45. Lepojarvi S, Pakarinen H, Savola O, *et al*. Posterior translation of the fibula may indicate malreduction: CT study of normal variation in uninjured ankles. *J Orthop Trauma* 2014;**28**(4):205–9.
46. Kane JM, Coleman S, Brodsky JW. Kinematics and function of total ankle replacements versus normal ankles. *Foot Ankle Clin* 2017;**22**(2):241–9.
47. Michael JM, Golshani A, Gargac S, *et al*. Biomechanics of the ankle joint and clinical outcomes of total ankle replacement. *J Mech Behav Biomed Mater* 2008;**1**(4):276–94.