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Anatomical analysis of the lateral ligament complex in the neutral position and during plantar flexion

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Abstract

Aim The purpose of this study was to obtain anatomical information on the anterior talofibular ligament (ATFL), anterior tibiofibular ligament (ATiFL) and calcaneofibular ligament (CFL) in the neutral position and during plantar flexion.

Methods Seventy specimens with whole ankle ligaments were recorded for anatomy education. ATFLs with single, double, and triple bands corresponded to Types A, B, and C. In our study, different types of ATFLs with information on the length, width, ATFL/CFL angle, ATFL/ATiFL angle, and the distance of the fibular center of insertion (fCOI) of ATFL-CFL-ATiFL in the neutral position and 20° plantar flexion, was collected.

Results In Type B, the length, width, and ATFL/ATiFL angle of the superior and inferior bands varied (length, $P<0.001$; width, $P<0.001$; ATFL/ATiFL angle, $P<0.001$). Among the types, the total widths of Types A/B and A/C were significantly different ($P<0.01$; $P<0.001$). In terms of postural changes, significant differences in the ATFL/ATiFL angle were observed for Type A ($P<0.001$), Type B ($P<0.001$), and Type C ($P<0.01$).

Conclusions In conclusion, attention should be given to the ATFL widths of different ATFL types during surgical treatment because of the significant differences among the three ATFL types. The relative independence of ATiFL and the cooperative relationship between ATFL and CFL are instructive for different ATFL surgical procedures. The ATFL, CFL, and ATiFL data can be used for anatomical reconstruction and secondary proofreading for ATFL injury or chronic ankle instability.

Keywords Anterior talofibular ligament (ATFL), Ankle ligament repair, Anatomy, Anterior tibiofibular ligament (ATiFL), Calcaneofibular ligament (CFL)

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Introduction

Since the anterior talofibular ligament (ATFL) is the weakest ligament of the lateral ligament complex with the lowest ultimate load, the ATFL is particularly susceptible to injury to the lateral malleolus [1, 2]. In contrast, 50%–70% of calcaneofibular ligaments (CFLs) are involved in such injuries [3]. The repair and reconstruction of the ATFL play important roles in the clinical process, and the options for treating ATFL have become a major issue for surgeons. There are three main surgical procedures for ATFL injury: nonanatomic tenodesis reconstruction, anatomic repair, and anatomic reconstruction [4]. To the best of our knowledge, both nonanatomic tenodesis reconstruction and ligamentous reconstruction are warranted, and no long-term studies favor one surgical procedure over the other. Although the choice of ATFL surgical treatment is ambiguous, the utilization of tendons is unamiable for primary repair because of their different biological roles than those of ligaments [5–8]. The anterior tibiofibular ligament (ATiFL) is a strong multifascicular ligament that stabilizes anterior syndesmosis and has the same tissue origin as the ATFL [9]. Jarvela et al. [10] first described an open anatomical reconstruction in which the distal fascicle of the ATiFL was applied for the primary repair of a ruptured ATFL. It has been reported that ATiFL can be utilized in anatomical reconstruction with better functional outcomes and fewer complications [10, 11].

A large amount of information is currently available for ATFL treatment. Although numerous anatomical studies on ATFL have been performed in recent years, more detailed and precise anatomical information has not yet been described. For example, the angle between the ATFL and other ligaments is essential for surgeons, but few studies have reported anatomical data from healthy cadavers. Taser et al. [12] reported the angle between the ATFL and the CFL. The data of Yıldız and Yalcın [13] significantly varied from those of Raheem et al. [2] and Uğurlu et al. [14]. Changes in position can reflect the braking mechanism of the ATFL; however, the focus of most of the current studies has been on ATFL length and width, that of a few studies has been on angles at different positions, and the conclusions with respect to the angles are vague [15–18]. In addition, with the increase in the number of three ATFL bands reported, an increasing number of studies have indicated that ATFL has different biological functions among types [19, 20]. However, there is no consensus on whether the three types have different braking mechanisms or on their stability order. Thus, further studies with more precise ATFL data are needed.

To the best of our knowledge, systematic investigations of the distance between the fibular center of the ATFL and its adjacent ligaments are scarce [17]. Therefore, as ATFL injuries do not often combine with ATiFL injuries, ATiFL may have great potential to provide auxiliary data in secondary proofreading for anatomical reconstruction of the ATFL. The purpose of this study was to collect detailed anatomical information on the ATFL with its adjacent ligaments, which included the ATiFL and CFL, and to clarify the relationship of the quantitative data changes between the neutral position and 20-degree plantar flexion. We dissected 70 healthy cadavers, collected anatomical information from different ATFL types and compared the results with those of previous studies. These results provide a reference for reconstructing the ATFL and indicate the potential of employing the ATiFL to reconstruct the ATFL, which can provide surgeons with better approach options for ATFL treatment.

Methods

Specimen preparation

The specimens were provided by the Department of Anatomy, Southern Medical University. After elimination of the ankles with a history of injury and deformity, 70 healthy specimens with complete ankle ligaments were included in our study. There was no attempt to distinguish whether the specimens were obtained from males or females. After the skin, fascia and retinaculum were removed, the ankle joint capsule was dissected carefully. Deep muscles, tendons, nerves, and blood vessels were removed cautiously to expose the ATF, CFL, ATFL-CFL connecting tissues, and tibiofibular ligaments gently by using tweezers and scalpels. The whole process had to maintain the integrity of the ligament fibers. Additionally, the fibular and tala attachments of the ATFL, the fibular and calcaneus attachments of the CFL, and the fibular and tibial attachments of the ATiFL were clearly exposed for measurement. All dissections were performed by anatomical technicians with at least 10 years of professional dissection training. All the specimens were loaded into a custom fixture, where screws were placed through the tabia, calcaneus and distal phalanges to ensure rigid fixation of the ankle to prevent movement during measurement. Neutral alignment in plantar flexion was achieved with a goniometer.

Anatomical measurement

Each ankle was classified by the number of bands in the ATFL. Single bands, double bands and triple bands corresponded to Type A, Type B, and Type C, respectively. A YLD-261 electronic digital Vernier caliper, two Kirschner wires, and an electronic digital angle ruler were used for the measurements. 1) ATFL length was measured from the midpoint of the fibular insertion site to the midpoint of the tala insertion site. 2) ATFL width was the average measurement collected at three points, which included the proximal insertion site, distal insertion site, and midway between two sites. 3) The angle between the ATFL and the CFL and between the AiTFL and the CFL was measured by drawing two intersecting lines through the origin point and the end point of each ligament. Because the angle was too small to accurately measure, two Kirschner wires were used to assist with the procedure. The length, width, and angle data were measured at both the 90-degree neutral position and the 20-degree plantar fixation position. 4) The center of insertion (COI) was marked, and the distances among the ATFL fibular COI, AITFL fibular COI, and CFL fibular COI were measured at a 90-degree neutral position.

To accurately set the ankle joint at 90-degree neutral and 20-degree plantar flexion positions, we combined a goniometer, reference marks, and a custom fixture. First, the goniometer was aligned with the center of the ankle, adjusting the foot until it reached 90 degrees (neutral position). Reference lines were then drawn on the calf and foot for visual guidance. A fixture secured the joint to prevent movement during the measurements. For the 20-degree plantar flexion position, the angle was adjusted using the goniometer and verified with reference marks before fixation. This method ensured precise and consistent positioning throughout the experiment.

In addition, to ensure the quality of the measurements, this study involved three measurers working on two teams collaboratively: two operators were responsible for angle adjustment and marking, whereas a technician was in charge of supervision and verification of the measurement results. Throughout the measurement process, the technician guided and confirmed each step according to standard operating procedures, ensuring coordinated and unified operations among the three individuals. After each measurement, the technician reviewed the data again to eliminate any potential human errors, thereby effectively improving the accuracy and reliability of the measurements.

Statistical analysis

IBM SPSS Statistics 22.0 (IBM Corp.; New York, USA) was used to analyze the data. Data were assessed for symmetry and normality, and no evidence was found for deviations from normality. Each distance and angle, expressed as the mean ± standard deviation (SD), was measured three times to obtain a mean, followed by the intraclass correlation coefficient (ICC) of the interobserver and interobserver data to evaluate their reliability. A P value < 0.05 indicated statistical significance.

Results

Our results show that the ATFL length is 17.8 ± 4.3 mm, the ATFL width of each band is 5.7 ± 2.1 mm, the ATFL total width is 11.3 ± 2.6 mm, the ATFL/CFL angle is 101.7 ± 10.6°, the ATFL/ATiFL angle is 45.8 ± 9.6°, the distance of the fibular center of insertion (fCOI) of ATFL-CFL is 12.8 ± 2.7 mm, the fCOI of ATFL-ATiFL is 17.9 ± 3.2 mm, and the fCOI of CFL-ATiFL is 27.3 ± 4.0 mm.

The three types of ATFLs include Types A, B, and C with single, double, and triple bands, respectively (Figs. 1, 2 and 3). Among the 70 ankles, 55 (78.6%) are Type B, 8 (11.4%) are Type A, and 7 (10.0%) are Type C.

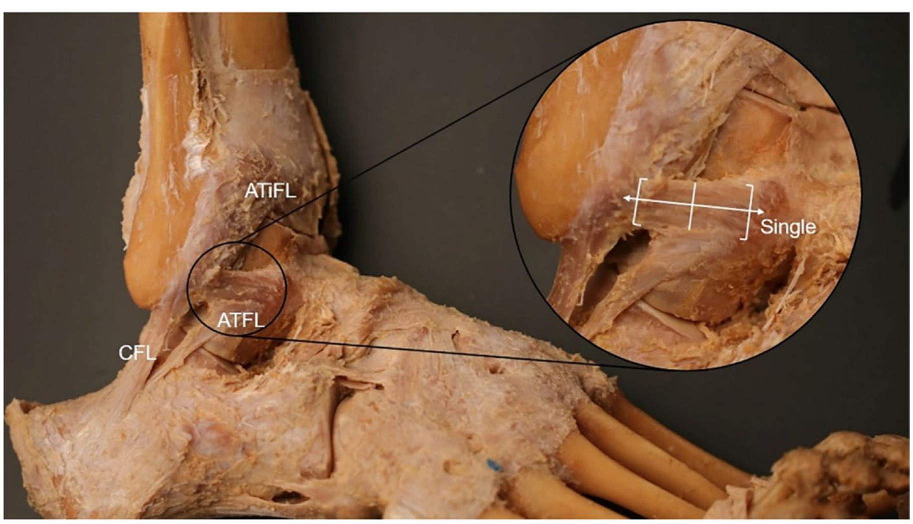

Fig. 1 The macro (left) and detailed (right) morphology of the Type A ATFL with its adjacent ligaments (ATiFL, CFL) are shown. ATFL length was measured from the midpoint of the fibular insertion site to the midpoint of the tala insertion site (solid white arrow). The ATFL width was the average measurement collected at three points, which included the proximal insertion site, the distal insertion site, and midway between the two points (solid white line)

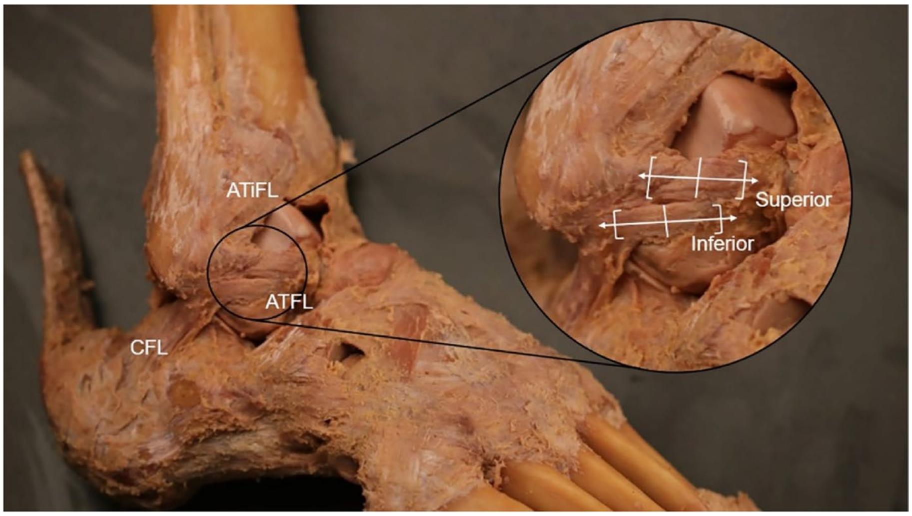

Fig. 2 The macro (left) and detailed (right) morphology of the Type B ATFL with its adjacent ligaments (ATiFL, CFL) are shown. The ATFL superior length and inferior length were measured from the midpoint of the fibular insertion site to the midpoint of the tala insertion site (solid white arrow). The ATFL superior width and inferior width were the average measurements collected at three points of each band, which included the proximal insertion sites, the distal insertion site, and midway between the two (solid white line)

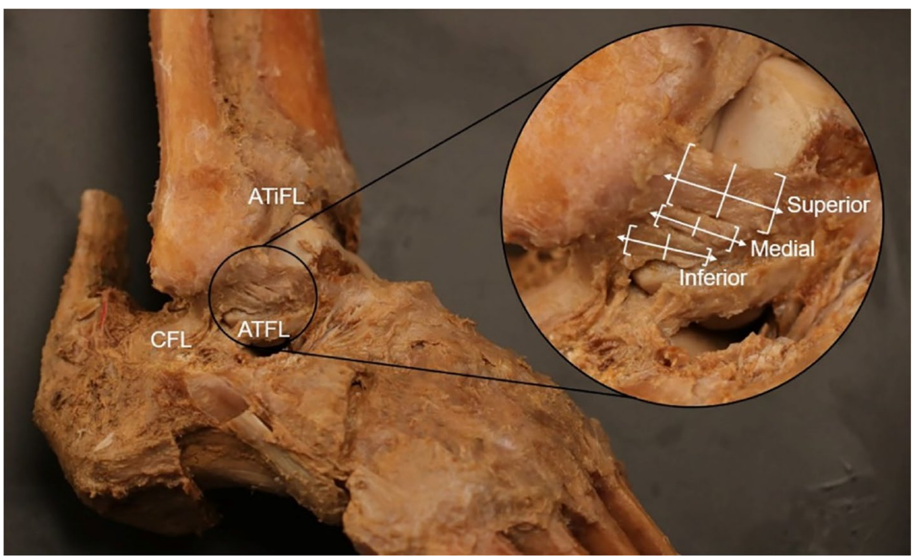

Fig. 3 The macro (left) and detailed (right) morphology of the Type C ATFL with its adjacent ligaments (ATiFL, CFL) are shown. The ATFL superior length, medial length and inferior length were measured from the midpoint of the fibular insertion site to the midpoint of the tala insertion site (solid white arrow). The ATFL superior width, medial width and inferior width were the average measurements collected at three points of each band, which included the proximal insertion sites, the distal insertion site, and midway between the two (solid white line)

Table 1 lists the ATFL length, width, ATFL/CFL angle (Fig. 4), and ATFL/ATiFL angle (Fig. 5) of each band in each type. Our results show that in Type B, the length, width and ATFL/ATiFL angle of the superior/inferior band are significant ($P < 0.001$), whereas the ATFL/CFL angle of the superior/inferior band does not vary ($P > 0.05$). In Type C, the ATFL length, width, ATFL/CFL angle and ATFL/ATiFL angle of the superior/median/inferior band do not vary ($P > 0.05$).

Table 2 shows the anatomical data of each ATFL type. The tendency of ATFL length and width suggests that the ATFL morphology of Types A to C changes from long and narrow to short and wide. Among the three types, there is no obvious change pattern in the ATFL/CFL/

Table 1 Quantitative data measured by each bundle band of ATFL with CFL and ATiFL in the neutral position

ATFL types	Number	ATFL length	ATFL width (each)	ATFL/CFL angle	ATFL/ATiFL angle
A	8	19.7 ± 2.2	8.6 ± 2.1	99.3 ± 13.5	45.3 ± 9.5
B/sup	55	**19.8 ± 3.6***	**6.9 ± 1.7***	102.9 ± 9.3	**41.2 ± 8.5***
B/inf	55	**16.0 ± 3.7***	**4.6 ± 1.6***	101.6 ± 13.8	**48.9 ± 10.4***
C/sup	7	17.6 ± 4.6	5.2 ± 1.5	101.8 ± 5.6	44.3 ± 11.2
C/med	7	17.4 ± 6.1	4.0 ± 1.7	96.4 ± 8.2	51.8 ± 8.7
C/inf	7	14.8 ± 5.3	4.1 ± 1.8	101.6 ± 14.7	54.6 ± 12.4
Avg ± SD		17.8 ± 4.3	5.7 ± 2.1	101.7 ± 10.6	45.8 ± 9.6

* $P < 0.05$

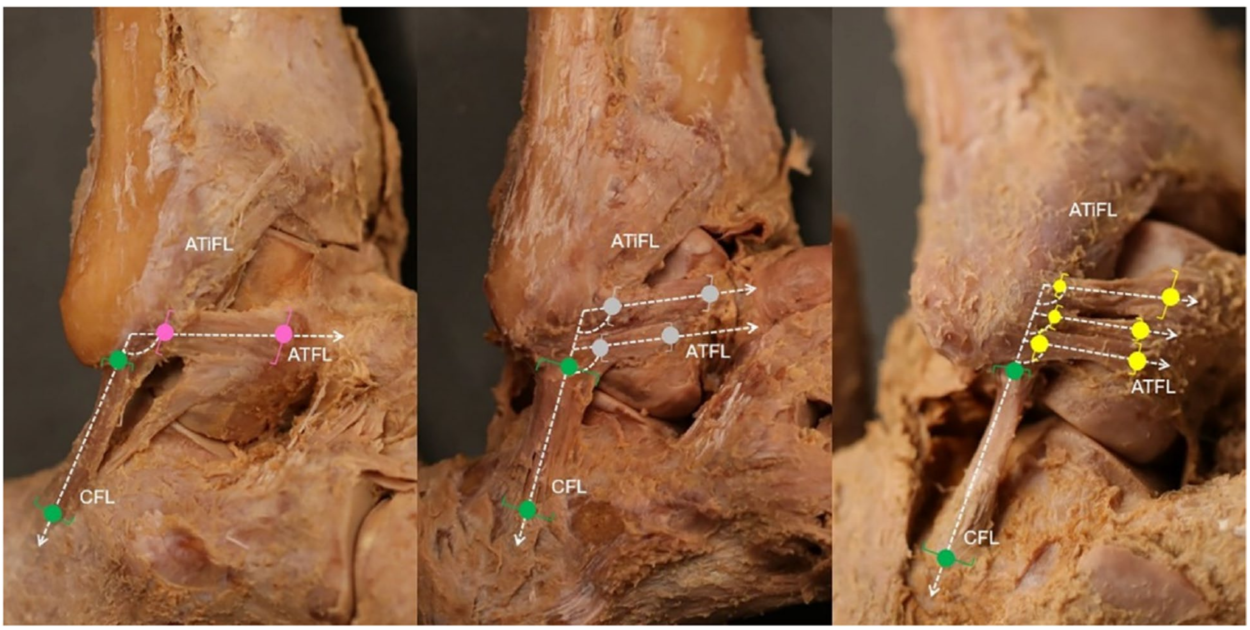

Fig. 4 A diagram of the ATFL/CFL angle measurement of the ATFL is shown. The CFL widths of the fibula attachment and calcaneal attachment (solid green line) as well as the midpoints of their widths (green dots), Type A ATFL fibular attachment and talus attachment (solid pink line) as well as the midpoints of their widths (pink dots), Type B ATFL fibular attachment and talus attachment (solid gray line) as well as the midpoints of their widths (gray dots), and Type C ATFL fibular attachment and talus attachment (solid yellow line), as well as the midpoints of their widths (yellow dots), are marked in the picture. Lines are drawn between the midpoint of two attachments in each ligament, and the intersection of the ATFL and CFL lines is regarded as the ATFL/CFL angle (white dotted line)

ATiFL angle. For the average fibular center of the insertion distance, the tendency of fCOI (ATFL-CFL) < fCOI (ATFL-ATiFL) < fCOI (ATiFL-CFL) was found for all three types (Figs. 6 and 7).

Table 3 displays the differences in ATFL length, width, ATFL/CFL angle and ATFL/ATiFL angle between the neutral position and plantar flexion. The three ATFL types do not differ in ATFL length ($P > 0.05$), width ($P > 0.05$) or ATFL/CFL angle ($P > 0.05$). Importantly, as shown in Table 3, for all ATFL types, the ATFL/ATiFL angles significantly changed (type A, $P < 0.01$; type B, $P < 0.001$; type C, $P < 0.01$). The results suggest that ATiFL is relatively independent and that the ATFL/ATiFL angle is highly flexible. Moreover, the negative variations in ATFL length, ATFL width and ATFL/CFL angle indicate the causes of ATFL injury with the CFL.

Discussion

There are numerous anatomical studies on ATFLs to better approach ATFL treatment. A previous morphological description of ATFL in which the number of bands was investigated. Three types of ATFLs were observed in our 70 ankle specimens:8 Type A (11.4%), 55 Type B (78.6%), and 7 Type C (10.0%). The ATFL length and width

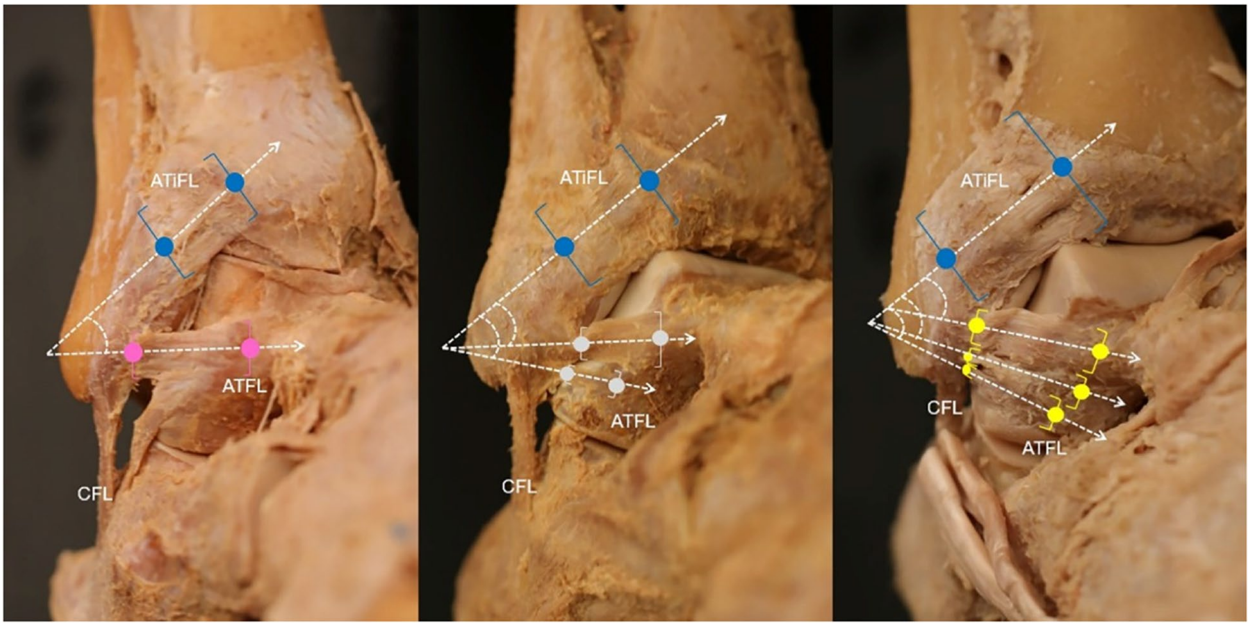

Fig. 5 A diagram of the ATFL/ATiFL angle measurement of the ATFL is shown. The ATiFL width of the fibula attachment and tabia attachment (solid blue line) as well as the midpoint of their width (blue dot), Type A ATFL fibular attachment and talus attachment (solid pink line) as well as the midpoint of their width (pink dot), Type B ATFL fibular attachment and talus attachment (solid gray line) as well as the midpoint of their width (gray dot), Type C ATFL fibular attachment and talus attachment (solid yellow line) and the midpoint of their width (yellow dot) are marked in the picture. Lines are drawn between the midpoint of two attachments in each ligament, and the intersection of the ATFL and ATiFL lines is regarded as the ATFL/ATiFL angle (white dotted line)

Table 2 Quantitative data measured by three types of ATFL, CFL and ATiFL in the neutral position

ATFL types	ATFL length	ATFL width (total)	ATFL/CFL angle	ATFL/ATiFL angle	ATFL-CFL COI	ATFL-ATiFL COI	ATiFL-CFL COI
A	19.7 ± 2.2	**8.6 ± 2.1**[a]	99.3 ± 13.5	45.3 ± 9.5	12.9 ± 1.9	17.9 ± 3.9	26.7 ± 4.5
B	17.9 ± 4.1	**11.5 ± 2.4**[a]	102.2 ± 11.9	45.1 ± 10.2	12.8 ± 2.9	18.0 ± 3.0	27.5 ± 3.9
C	16.6 ± 5.5	**13.3 ± 1.8**[a]	99.9 ± 10.6	50.2 ± 11.8	12.8 ± 1.8	17.4 ± 3.6	26.6 ± 3.6
Avg ± SD	17.8 ± 4.3	11.3 ± 2.6	101.7 ± 10.6	45.8 ± 9.6	12.8 ± 2.7	17.9 ± 3.2	27.3 ± 4.0

[a] $P < 0.01$

have been extensively investigated in anatomical studies (Table 4). The mean ATFL length measured in our study was 17.8 ± 4.3 mm, which is similar to the length reported by Siegler et al. [21], Luo et al. [22], and McDermott et al. [23]. Our measured length was slightly shorter than those reported by Taser et al. [12] and Jorge et al. [24] but slightly longer than those reported by Raheem et al. [2] and Milner and Soames [25]. Neuschwander et al. [26] reported the lengths of the superior and inferior bands, and our results are consistent with the previous results. The lengths reported by Burks et al. [19] and Yildiz and Yalcin [13] differ from those reported by other investigators, with the measurements being of the longest fibers of the ligament, which differ from the insertion site to the insertion site.

With respect to the angle between the ATFL and other ligaments, investigations of the angle between the lateral ligaments between the ATFL and the CFL have been limited in most studies [2, 12–14, 28]. In the research performed by Han et al. [28], the coefficient of variation of the ATFL/CFL angle was lowest in different populations compared with ATFL length, width, thickness, etc., suggesting that the angle between ligaments might provide reliable proofread data for ligament anatomical repair [28]. In previous studies, angle measurements were taken by Taser et al. [12] Yıldız and Yalcın [13] differed from Raheem et al. [2] and Uğurlu et al. [14]. We share similar ATFL/CFL angle data with those of Taser et al. [12], Yıldız and Yalcın [13]. Our results show that the mean ATFL/ATiFL angle of the three types is 45.8 ± 9.6°,

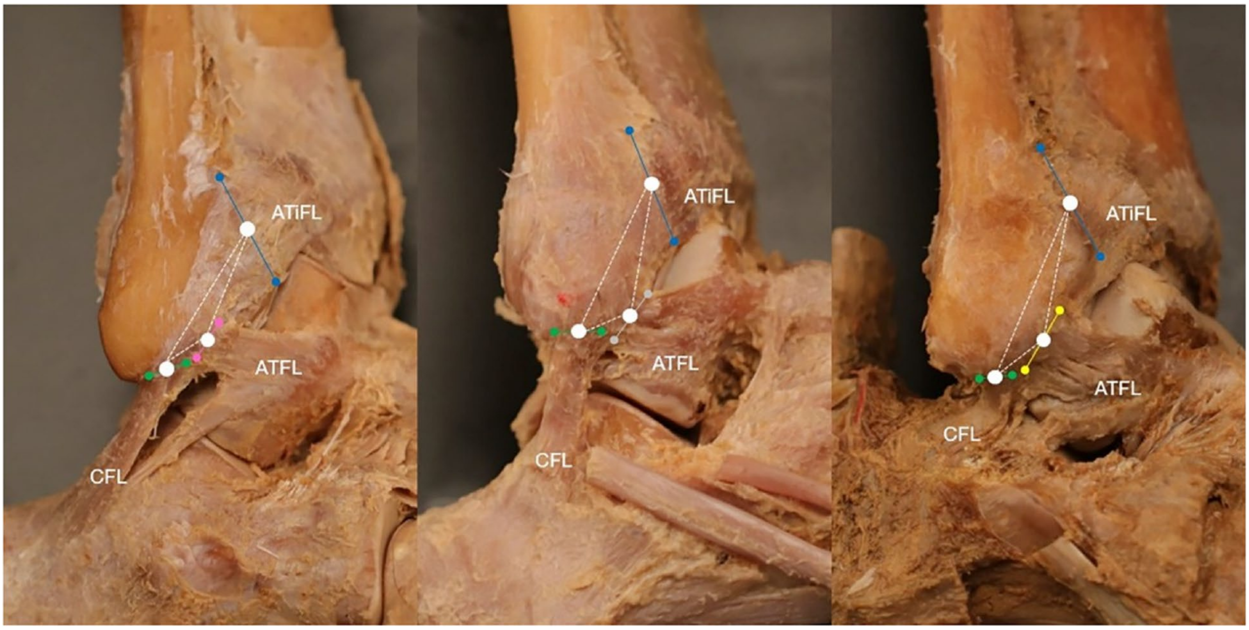

Fig. 6 A diagram of the distance among the ligamentous fibular centers of insertion (fCOIs) of the ATFL is shown. The CFL fibular insertion width (solid green line), Type A ATFL fibular insertion width (solid pink line), Type B ATFL fibular insertion width (solid gray line), Type C ATFL fibular insertion width (solid yellow line) and ATiFL fibular insertion width (solid blue line) are shown. The fCOI is noted in ATFL, CFL and ATiFL (white dots), and the distances among each fCOI are marked (white dotted line)

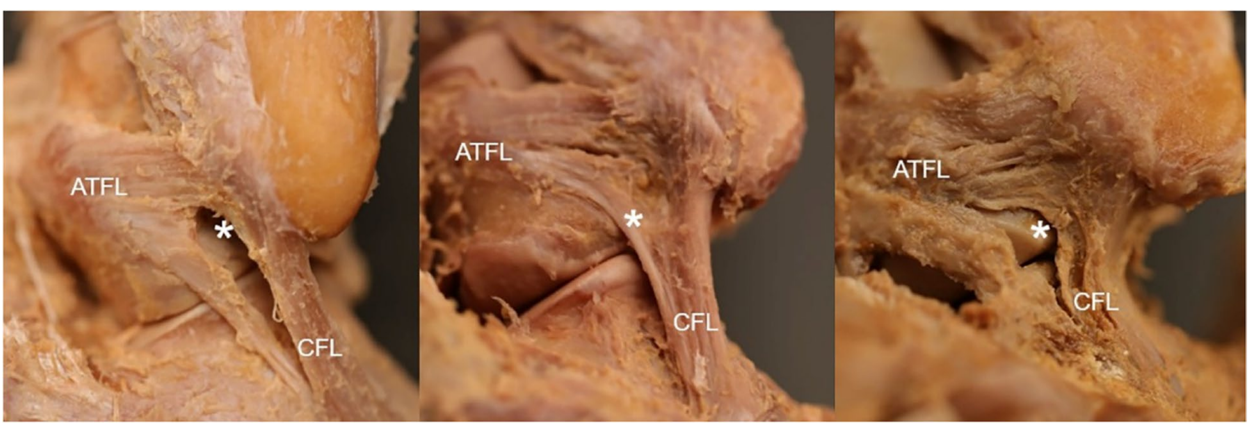

Fig. 7 The asterisks from left to right show connecting tissue between the CFL and ATFL types A, B, and C, respectively

which is slightly smaller than that reported by the previous author [14]. The ATFL/ATiFL angle in healthy ankle specimens is essential for clinical practice, such as for the treatment of tibiotalar impingement syndrome by resecting ligamentous tissues and secondary proofreading for reconstruction of the ATFL [29–32]. Compared with those of previous studies, our results are more detailed because of the inclusion of different ATFL types, and the angle data can be used as the basis for secondary proofreading after surgical treatment.

With respect to the function of the ATFL and its types, recent studies have shown that three types of ATFLs share different ankle braking functions [15–18]. In some quantitative analyses, Edama et al. [15] reported that the ATFL inferior band length was significantly shorter ($P < 0.05$) than that in the superior band in Type B-a and Type B-b, and the ATFL inferior band width was significantly narrower ($P < 0.05$) than that in the superior band in Type B-a and Type B-b. our results were similar to those of Edama et al. [15] for Type B (Table 1). Additionally, in

Table 3 Variations in the ATFL length, ATFL width, ATFL/CFL angle, and ATFL/ATiFL angle between the neutral position and 20° plantar flexion

		Type I	Type II	Type III
ATFL length	Neutral position	19.7 ± 2.2	17.9 ± 4.1	16.6 ± 5.5
	Plantar flexion	20.6 ± 2.0	18.1 ± 4.3	17.8 ± 5.7
	***P* value**	**0.4372**	**0.7664**	**0.8510**
ATFL width (total)	Neutral position	8.6 ± 2.1	11.5 ± 2.4	13.3 ± 1.8
	Plantar flexion	8.5 ± 2.5	11.7 ± 2.3	13.2 ± 1.6
	***P* value**	**0.8884**	**0.6543**	**0.9403**
ATFL/CFL angle	Neutral position	99.3 ± 13.5	102.2 ± 11.9	99.9 ± 10.6
	Plantar flexion	104.5 ± 12.2	103.4 ± 9.4	101.8 ± 10.0
	***P* value**	**0.4646**	**0.3893**	**0.7098**
ATFL/ATiFL angle	Neutral position	45.3 ± 9.5	45.1 ± 10.2	50.2 ± 11.8
	Plantar flexion	63.1 ± 12.8	57.8 ± 8.7	62.2 ± 13.4
	***P* value**	**0.0045***	**< 0.0001***	**0.0037***

[*] $P < 0.05$

their study, the ATFL widths of the intermediate band and inferior band were significantly narrower ($P < 0.05$) than those of the superior band in Type C. In contrast to the results of Edama et al. [15], our results revealed no significant differences among the three bands of Type C ATFLs. According to the quantitative analysis results for ATFL length and width, Edama et al. [15] demonstrated that the length and width of type III ATFL were weaker than those of type A and type B ATFLs. Our data revealed that only the type B ATFL length and width significantly differed between the superior band and the inferior band (Table 1). The difference may be related to the number of specimens and the method of measurement.

Furthermore, these findings indicate that the adaptability, flexibility, and protection of the talus in Type B specimens are better than those in the other types. In type B, the results are consistent with the trending consensus that the superior bundle and inferior bundle have different braking functions [15–18]. This may be due to morphological evidence that the superior fascicle of the ATFL is an intraarticular structure of the ankle, whereas the inferior fascicle of the ATFL is an extraarticular structure [15]. Kobayashi et al. [18] reported that the inferior length was significantly shorter in Type B and Type C than in Type A ($P < 0.001$). Conversely, our results revealed no difference in ATFL length among the

Table 4 Comparison of ATFL quantitative data from previous studies

Previous study	ATFL length (mm)	ATFL width (mm)	ATFL/CFL angle (degree)	ATFL/ATiFL angel (degree)
Siegler et al. [21]	17.81 ± 3.05	-	-	-
Burks et al. [19]	Longest: 24.8	7.2	-	-
Luo et al. [22]	19.6 ± 2.2	-	-	-
Milner and Soames [25]	13.0 ± 3.9	11.0 ± 3.3	-	-
McDermott et al. [23]	19 ± 9.4	-	-	-
Taser et al. [12]	22.37 ± 2.50	Proximal: 10.77 ± 1.56 Meddle: 6.75 ± 2.89 Distal: 10.96 ± 2.38	132° (118–145°)	-
Uğurlu et al. [14]	14.38–20.84	7.61–12.98	13°	68°
Raheem et al. [2]	15.5 ± 7.7 (10–21)	10.0 ± 7 (5–15)	12° ± 5.6 (8–16)	-
Neuschwander et al. [26]	SB: 19.7 ± 1.2 IB: 16.7 ± 1.1	-	-	-
Yildiz and Yalcin [13]	Shortest: 12.24 ± 1.99 Longest: 14.19 ± 2.02	11.07 ± 5.63	Right: 112° ± 14 Left: 106° ± 19	-
Wenny et al. [27]	proximal/posterior: 12.85 ± 2.64 plantar/anterior: 11.38 ± 2.25	talar/calcaneal: 6.62 ± 1.39 fibular/tibial: 6.50 ± 1.51	-	-
Jorge et al. [24]	21 ± 4 (13–29)	-	-	-
Edama et al. [15]	I: 21.3 ± 2.8 II-a: 19.6 ± 2.2 II-b: 20.9 ± 3.5 III: 20.4 ± 3.1	I: 11.1 ± 2.7 II-a: 13.8 ± 3.0 II-b: 13.3 ± 2.5 III: 13.9 ± 2.9		
Kobayashi et al. [18]	I: 23.9 ± 3.5 II: 19.8 ± 3.5 III: 18.6 ± 2.5	I: 8.4 ± 2.3 II: 12.1 ± 3.0 III: 12.6 ± 1.8	-	-

ATFL types (Table 2). Our results are consistent with this finding and show that the widths in Types B and C are significantly narrower than those in Type A (Table 2). Compared with the conclusions by Kobayashi et al., our study indicates that the different braking mechanisms in different band types may have a strong relationship with the total width, with significant differences among types [18]. The ATFL width is the attachment distance between the ligaments of the talus side and the fibula side. It affects the extent of encapsulation of the talus together with length. The better the protection of the talus by a suitable covering area is, the less ligament instability there will be.

The avulsion of the ATFL can easily combine with the CFL and its fibular attachment side [3]. The mechanism of the combination of ATFL and CFL injury may be related to the ATFL–CFL connecting tissue within the ATFL and CFL (Fig. 7). In recent years, several studies have reported that arciform fibers uniting the ATFL and CFL may act as a ligamentous complex [2, 9, 13, 16, 17, 19, 33]. Kakegawa et al. [18] reported that connecting fibers may have only a small control function. In contrast, Vega et al. [34] and Cordier et al. [33] reported that the ATFL, CFL, and ATFL-CFL arciform fibers work together as functional units that could play a mechanical role in transferring tension between two ligaments and could allow them to work in tandem in stabilizing the ankle and subtalar joints. Our dynamic investigation of the ATFL with the CFL supports the conclusions obtained by Vega et al. and Cordier et al. In a previous anatomical study, Raheem et al. [2] reported that the angle between the ATFL and the CFL was similar in terms of plantar flexion and dorsi flexion. In our study, compared with the ATFL/ATiFL angle, no significant difference was detected in the ATFL/CFL angle between the neutral position and plantar flexion position (Table 3). Our results can be explained by the fact that in the case of a community complex, the tension transfer mode of one structure is similar. Additionally, Edama et al. [15, 16] suggested that Type C ATFLs and CFLs cooperate in ankle bracing. Unlike in previous studies, no significant difference in angle changes was detected among the different types in our study, suggesting that not only Type C but also Types A and B are able to cooperate with the CFL.

The anterior tibiofibular ligament (ATiFL) is a multifascicular ligament that works as the anterior stabilizer for tibiofibular syndesmosis [30]. The ATiFL distal fascicle has many of the same anatomical characteristics as the superior fascicle of the ATFL, including close fibular attachment, intraarticular structure, and continuity of fibular origins [29, 31, 35]. From an ATiFL functional point of view, Nikolopoulos et al. [29] reported that the ATiFL distal fascicle does not affect joint stability after resection. Furthermore, Rasmussen et al. [32] reported that external rotation increased by a mean of only 1.5° after iatrogenic transection of the ATiFL, suggesting that the ATiFL had a minimal contribution to lateral ankle stability; our data confirm the same conclusion. As mentioned earlier, the statistical differentiation of ATFL/CFL angle changes ($P > 0.05$, Table 3) may indirectly reflect tension transmission. Compared with ATFL/CFL angle changes ($P < 0.01$, Table 3), we speculate that little or no tension is transferred from ATiFL to ATFL from a new anatomical point of view.

Clinically speaking, this relatively independent mechanism does support the use of ATiFL. Following the advancements in ATFL anatomical reconstruction methods, the development of arthroscopic technology, the advantage of the same tissue homology, less trauma, the avoidance of tendon harvesting or allografts, and the use of ATiFLs to rebuild ATFLs may be promising prospects. Jarvela et al. [10] first described an open reconstruction method using the distal fascicle of the ATiFL for the anatomical reconstruction of the ATFL when the local ligament tissue is severely damaged and augmentation reconstruction is necessary. Furthermore, Vega et al. [9] reported successful results after performing Jarvela's anatomical reconstruction by applying the all-arthroscopic method, suggesting that the ATiFL transferred ligament can be used as a biological reinforcement for ATFL repair. However, surgical intervention cannot avoid the risk of altering the physiological immobilization mechanisms of the two ligaments. Nevertheless, our normal ATFL with ATiFL data provide a secondary proofreading for applying ATiFL to ATFL augmentation reconstruction.

The insertion points and relative positions of the ATFL, CFL, and ATiFL are essential for anterolateral stability of the subtalar joint [17]. Previous studies reported difficulty in recognizing the exact attachment of the ATFL and CFL, and bony landmarks were introduced to locate the ligaments [17]. The tips of the lateral malleolus (IT), the articular tips of the fibula (AT), and the fibular obscure tubercle (FOT) are three main bony landmarks of the lateral ligaments. Matsui et al. [20] first reported the existence of the fibular obscure tubercle (FOT) as a clinically reliable bony landmark of the ATFL and CFL origin locations of the fibula. However, subsequent research revealed that the FOT is located proximally close to the fibular attachments of the ATFL and CFL (Table 5) and that it cannot be manually detected in all patients; the IT has become the most commonly used bony landmark [19, 27, 36–39]. Although AT was introduced by some authors, the frequency of applying this bony landmark is quite low [18, 28]. Understandably, if ligament injury is combined with severe bony avulsion fracture, reference to bony landmarks may interfere. Additionally, in previous

Table 5 Distances between different bony landmarks/fCOIs of ligaments and the fCOIs of ligaments

	ATFL	Intersection points of ATFL and CFL	CFL	ATiFL
Our study	-	-	ATFL: 12.8 ± 2.7 mm -	ATFL: 17.9 ± 3.2 mm CFL: 27.3 ± 4.0 mm
Burks et al. [19]	IT: 10.1 mm	-	-	-
Clanton et al. [36]	IT-single: 13.8 mm IT-sup double: 16.3 mm IT-inf double: 10.2 mm	-	-	-
Wenny et al. [27]	IT: 0.58 ± 1.89 mm	-	IT: 0	IT: 25.45 ± 5.84 mm
Khawaji and Somes [37]	IT: > 10 mm	-	-	-
Williams et al. [39]	-	-	-	IT: 30.5 mm (28.5–32.4)
Thes et al. [38]	IT: > 16 mm	-	IT: > 4 mm	-
Matsui et al. [20]	FOT: 3.7 mm	FOT: 2.4 mm	FOT: 4.9 mm	-
Kakegawa et al. [17]	IT: 14.3 ± 1.9 mm AT: 4.3 ± 1.1 mm	-	IT: 7.4 ± 1.7 mm AT: 7.6 ± 1.6 mm ATFL: 7.1 ± 1.4 mm	-
Park et al. [40]	-	IT: 12.0 ± 2.5 mm	-	-
Han et al. [28]	-	-	AT: 4.94 ± 1.7 mm	-

The tip of the lateral malleolus = IT; Fibular obscure tubercle = FOT; Articular tips of the fibula = AT

studies, some data concerning the distance between the osseous landmarks and the ATFL fibular attachment differed substantially among scholars (Table 5). Furthermore, we believe that most studies are limited to bony landmarks and overlook the distance between the attachments of ligaments. To remedy this data weakness and for better surgical treatment, we added more anatomical information about the distance among fibular attachments for secondary proofreading (Tables 2 and 4).

In conclusion, the ATFL with adjacent ligament data can be used for anatomical reconstruction and secondary proofreading. The Type II ATFL is more flexible than Types I and III. Additionally, the ATFL total width varies among types, which may contribute to the different bracing functions among ATFL types, indicating that attention should be given to ATFL total width in surgical treatment. In addition, ATFL and CFL can be seen as functional units, whereas ATiFL is relatively independent of ATFL, supporting the clinical use of ATiFL to reconstruct ATFL on the basis of applying ATiFL anatomical data with ATFL for auxiliary proofreading.

Abbreviations

ATFL Anterior talofibular ligament
ATiFL Anterior tibiofibular ligament
CFL Calcaneofibular ligament
fCOI Fibular center of insertion
FOT Fibular obscure tubercle
IT Inferior tips
AT Articular tips
COI Center of insertion

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Use of AI
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The authors report that there are no competing interests to declare.

Informed consent
All donors provided written informed consent for the collection and use of their specimens for medical research or teaching.

Authors' contributions
C.X., J.O., and J.D. conceived and designed the experiments. Z.C., H.Y., X.Z., M.S., Z.L., C.L., Z.X., H.L., and G.X. performed the experiments. Z.C., H.Y., X.Z., and M.S. analysed the data. Z.C., H.Y., and X.Z. wrote the manuscript. C.X., J.O., and J.D. reviewed the manuscript. All authors agree to be accountable for the content of the work.

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Data availability
The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to aprticipate
This Ethics Committee of the School of Basic Medical Science, Southern Medical University, approved the study (No. NFYKDXJCYXY2019031001). All experimental methods and protocols performed in this study were in accordance with the relevant guidelines and regulations (Declaration of Helsinki).

Consent for publication
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