Effects of ligament sectioning on the kinematics of the distal tibiofibular syndesmosis

A radiostereometric study of 10 cadaveric specimens based on presumed trauma mechanisms with suggestions for treatment

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Background Syndesmotic injuries of the ankle without fractures can result from external rotation, abduction and dorsiflexion injuries. Kinematic studies of these trauma mechanisms have not been performed. We attempted to describe the kinematics of the tibiofibular joint in cadaveric specimens using radiostereometry after sequential ligament sectioning, and resulting from different trauma mechanisms and axial loading, in order to put forward treatment guidelines for the different types of syndesmotic injuries.

Methods We assessed the kinematics of the distal tibiofibular joint in fresh–frozen cadaveric specimens using radiostereometry in the intact situation, and after alternating and sequential sectioning of the distal tibiofibular and anterior deltoid ligaments. To assess which of the known trauma mechanisms would create the largest displacements at the syndesmosis, the ankle was brought into the following positions under an axial load that was comparable to body weight (750 N): neutral, dorsiflexion, external rotation, abduction, and a combination of external rotation and abduction.

Results In the neutral position, the largest displacements of the fibula consisted of external rotation and posterior translation. Loading of the ankle with 750 N did not apparently increase or decrease the displacements of the fibula, but gave a larger variety of displacements.

In every position, sectioning of a ligament resulted in some fibular displacement. Sectioning of the anterior tibiofibular ligament (ATiFL) invariably resulted in external rotation of the fibula. Additional sectioning of the anterior part of the deltoid ligament (AD) gave a larger variety of displacements. In general, sectioning of the posterior tibiofibular ligament (PTiFL) gave the smallest displacements. Combined sectioning of the ATiFL and the PTiFL resulted in a larger variety of displacements in the neutral position. Sectioning of the AD together with the ATiFL and PTiFL resulted in tibiofibular displacements in the neutral situation exceeding the maximum values found in the intact situation, the most important being fibular external rotation.

Interpretation Sectioning of the ATiFL results in mechanical instability of the syndesmosis. Of all trauma mechanisms, external rotation of the ankle resulted in the largest and most consistent displacements of the fibula relative to the tibia found at the syndesmosis. Based on our findings and the current literature, we recommend that patients with isolated PTiFL or AD injuries should be treated functionally when no other injuries are present. Patients with acute complete ATiFL ruptures, or combined ATiFL and AD ruptures should be treated with immobilization in a plaster. Patients with combined ruptures of the ATiFL, AD and PTiFL need to be treated with a syndesmotic screw.

The distal tibiofibular syndesmosis consists of an anterior part (the anterior inferior tibiofibular

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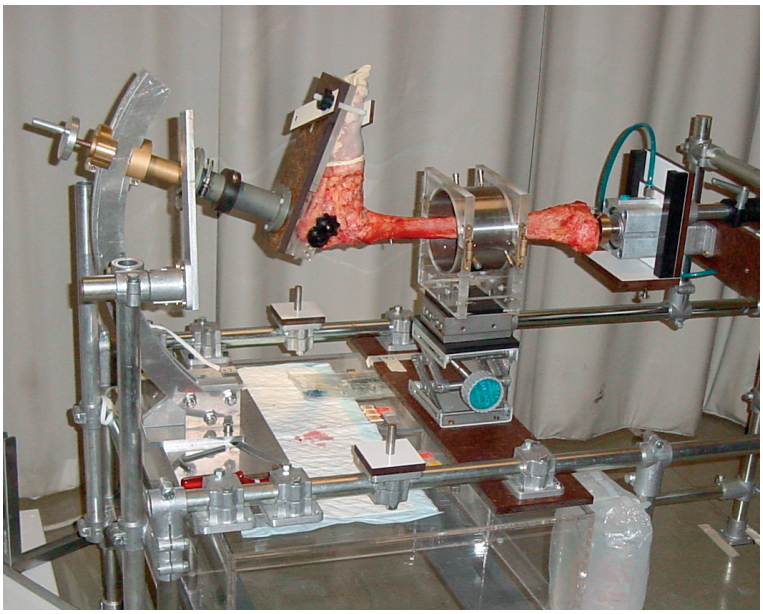
ligament; ATiFL), a posterior part (the posterior inferior tibiofibular ligament; PTiFL and a transverse ligament; TL) and in–between, the interosseous ligament (IL)—the most distal condensation of fibres of the interosseous membrane (Grath 1960).

According to Kelikian and Kelikian (1985), 3 types of syndesmotic injuries (or diastasis) without ankle fractures can be recognized. Most commonly, the ATiFL is ruptured. This anterior syndesmotic diastasis is an "open book" injury resulting from external rotation of the fibula. The ATiFL rupture may be combined with an injury of the deltoid ligament. Alternatively, a complete tibiofibular disruption of all 4 syndesmotic ligaments may result from abduction or external rotation. The third and least common variety is intercalary diastasis, which is seen in children. It results from a rupture of the interosseous membrane combined with a metaphyseal fracture of the fibula and a physeal fracture of the tibia. The above–mentioned injuries have also been recognized by others (Mullins and Sallis 1958, Rasmussen et al. 1982, Miller et al. 1995, Xenos et al. 1995). They are believed to result from external rotation, abduction and dorsiflexion injuries, or combinations of these (Lauge–Hansen 1950, Weber 1966, Frick 1978, Pankovich 1979, Colville et al. 1990). Kinematic studies—including those concentrating on these trauma mechanisms—are difficult to perform because displacements in the syndesmosis are usually small and are thus difficult to measure.

We assessed the kinematics of the tibiofibular joint in cadaveric specimens using radiostereometry (RSA) after sequential ligament sectioning and axial loading to simulate different trauma mechanisms, in order to put forward guidelines for the treatment of different types of syndesmotic injuries.



Testing device. The tibia is secured and the foot is attached to a plate, allowing full range of motion (example of maximal dorsiflexion).

Material and methods

10 fresh–frozen lower legs, sectioned through the knee, with a mean age of 88 (81–102) years were used. Only intact specimens at macroscopic and radiographical examination (conventional anterior-posterior and lateral views) were included. All soft tissues from knee to tarso–metatarsal joints, except the interosseous membrane and the ligaments and joint capsules, were removed. 5 tantalum markers (0.8 mm) were placed in the distal tibia and fibula according to a standard scheme to achieve optimal spreading.

The specimens were mounted on a device that secured the tibia and allowed full range of motion (Figure). The foot was attached to a plate, with fixation at the calcaneus and forefoot. The longitudinal axis of the tibia was positioned parallel to the ground surface. Before RSA examinations started, the range of motion of the ankle and foot complex was determined with a goniometer attached to the device. The neutral position (i.e. the starting position of this study) was set as a plantigrade ankle position with the intermalleolair line parallel to the ground. This position, instead of the zero position for the forefoot (American Academy of Orthopaedic Surgeons 1965), was chosen to minimize posi-

Table 1. The number of specimens in different positions and sectioning conditions

Position [a] and loading	Intact	Sectioning conditions [b] A	D	P	A+D	A+P	A+D+P
N	9	4	3	2	5	4	10
N loaded	10	4	3	2	5	5	10
ER	10	4	3	2	5	5	10
ER loaded	9	4	3	2	5	5	10
AB loaded	9	4	3	2	5	5	10
ER+AB loaded	9	4	3	1	5	5	10
DF loaded	7	4	3	2	5	5	10

[a] Positions:
N: Neutral,
ER: External rotation,
DF: Dorsiflexion.
AB: Abduction;
[b] Sectioning conditions:
A: ATiFL sectioned,
D: anterior part of deltoid ligament (AD) sectioned,
P: PTiFL sectioned.

tioning errors that could be the result of forefoot abnormalities.

RSA examinations were done, unloaded and under an axial load (L) that was comparable to body weight (750 N), in the following positions: neutral (N), maximal dorsiflexion (DF), maximal external rotation (ER), maximal abduction (AB) and a combination of the latter two (ER+AB), and for the following sectioning conditions: isolated sectioning of the ATiFL (A), isolated sectioning of the anterior deltoid ligament (D), isolated sectioning of the PTiFL and the transverse ligament (P), and combinations of these (Table 1). With a Vidar VXR–12 scanner (Vidar Systems Corp., Alleroed, Denmark), the radiographs were scanned at 150 d.p.i. and 8–bit gray scale resolution. They were digitally processed and analyzed (Valstar et al. 2000) using RSA–CMS software (Medis BV, Leiden, The Netherlands).

The motion of the fibula was expressed as translation and rotation of the fibula relative to the tibia. Positive directions for translations along the coordinate axes were lateral–medial, caudal–cranial, and posterior–anterior. Positive directions for rotations about the coordinate axes were plantar flexion, internal rotation, and adduction. Reliability of RSA depends on nonlinear marker distribution. The geometrical interpretation of the distribution of the markers in 3–D space is expressed in the condition number (Söderkvist and Wedin 1993). In accordance with international recommendations, examinations were included in the study when the condition number was below 80–90 (Börlin et al. 2002). Descriptive statistics and confidence limits were calculated with Stata software (StataCorp LP, College Station, Texas, USA).

Results

The mean ranges of motion of the ankle and foot complex were: dorsiflexion 18° (15–20); plantarflexion > 30°; internal rotation 2° (0–5); external rotation 19° (15–25); abduction 3° (0–5) and adduction 19° (15–25). The mean condition numbers for tibia and fibula were 24 (15–39) and 15 (10–17). No segment had to be excluded from analysis. The reproducibility, assessed by repeating 10 examinations of the intact situation and presented as SDs from zero, was 0.1 mm/0.2° (x–axis), 0.1 mm/0.3° (y–axis), 0.2 mm/ 0.1° (z–axis).

Displacements of the fibula with respect to the tibia (Tables 2–7)

All positions and conditions, except ER and some conditions of ER–L, resulted in an increase in tibiofibular width. ER and ER–L resulted in a decrease in width. Most positions and conditions resulted in cranial displacement of the fibula. Exceptions were found after P in most positions, as well as after P, A+D and A+D+P during N–L. DF–L and ER+AB–L resulted in posterior displacement of the fibula in all sectioning conditions. With the exception of P, larger posterior translations were found for ER and ER–L. All conditions of AB–L (except A+D) resulted in anterior translation. N–L resulted in a large variety of translations in all sectioning conditions. Displacements about the x–axis did not exceed 1 mm or 1° for any position or sectioning condition. Most positions and conditions resulted in external rotation. The most consistent exception was P, which resulted in internal rotation unless ER or ER–L was applied. N–L resulted in adduction, ER and most of ER–L in abduction, and the other positions and conditions gave diverse results. Mean rotations about the z–axis did not exceed 0.54º.

Table 2. Translation X: Lateral–medial displacement of the fibula relative to the tibia after transection of the tibiofibular and deltoid ligaments in different positions and loading conditions (mean and SD; relative to the intact neutral unloaded situation). Negative value = lateral displacement

	Translation X		
	Mean	SD	95% CI
Intact (n=10)			
N	–	–	
N loaded	–0.24	0.50	–0.63 to 0.14
ER	0.53	0.38	0.26 to 0.81
ER loaded	0.14	0.40	–0.16 to 0.45
AB loaded	–0.29	0.61	–0.76 to 0.18
ER+AB loaded	–0.04	0.80	–0.65 to 0.57
DF loaded	–0.81	0.73	–1.49 to –0.14
ATiFL sectioned (n=4)			
N	–0.01	–0.01	–0.16 to 0.14
N loaded	–0.52	–0.52	–1.10 to 0.06
ER	0.50	0.50	–0.06 to 1.06
ER loaded	–0.45	–0.45	–1.17 to 1.08
AB loaded	–0.42	–0.42	–1.03 to 0.20
ER+AB loaded	–0.26	–0.26	–0.86 to 0.33
DF loaded	–0.58	–0.58	–1.24 to 0.08
AD sectioned (n=3)			
N	–0.06	0.36	–0.95 to 0.82
N loaded	–0.57	0.63	–2.13 to 0.99
ER	0.00	0.80	–1.99 to 1.99
ER loaded	–0.27	0.35	–1.15 to 0.61
AB loaded	–1.09	0.70	–2.84 to 0.66
ER+AB loaded	–1.04	0.75	–2.91 to 0.82
DF loaded	–1.12	0.94	–3.44 to 1.21
PTiFL sectioned (n=2)			
N	–0.03	0.25	–2.25 to 2.18
N loaded	–0.58	0.18	–2.17 to 1.01
ER	0.50	0.80	–6.72 to 7.72
ER loaded	0.29	0.27	–2.43 to 2.49
AB loaded	–0.25	0.04	–4.86 to 4.36
ER+AB loaded	–0.34	–	–
DF loaded	–0.90	0.40	–4.51 to 2.72
ATiFL and AD sectioned (n=5)			
N	–0.05	0.34	0.22 to 0.54
N loaded	–0.16	0.73	–1.42 to 0.61
ER	0.67	0.36	0.16 to 0.88
ER loaded	0.27	0.28	–1.15 to 0.36
AB loaded	–0.13	0.70	–1.56 to 0.07
ER+AB loaded	0.14	0.57	–1.67 to 0.32
DF loaded	–0.58	0.20	–2.13 to 0.01
ATiFL and PTiFL sectioned (n=5)			
N	–0.05	0.34	–0.47 to 0.38
N loaded	–0.16	0.73	–1.32 to 1.00
ER	0.67	0.36	0.22 to 1.13
ER loaded	0.27	0.28	–0.08 to 0.61
AB loaded	–0.13	0.70	–1.00 to 0.73
ER+AB loaded	0.14	0.57	–0.76 to 1.05
DF loaded	–0.58	0.20	–0.83 to –0.33
ATiFL, AD and PTiFL sectioned (n=10)			
N	–0.08	0.68	–0.57 to 0.40
N loaded	–0.43	0.64	–0.89 to 0.03
ER	0.51	0.53	0.13 to 0.88
ER loaded	0.01	0.66	–0.46 to 0.48
AB loaded	–0.50	0.77	–1.05 to 0.05
ER+AB loaded	–0.32	0.78	–0.92 to 0.28
DF loaded	–0.69	0.71	–1.20 to –0.19

See Table 1 for abbreviations.

Table 3. Translation Y: Caudal–cranial displacement of the fibula relative to the tibia after transection of the tibiofibular and deltoid ligaments in different positions and loading conditions (mean and SD; relative to the intact neutral unloaded situation). Negative value = caudal displacement

	Translation Y		
	Mean	SD	95% CI
Intact (n=10)			
N	–	–	– –
N loaded	0.19	0.29	–0.29 to 0.41
ER	0.12	0.22	–0.30 to 0.28
ER loaded	0.40	0.42	0.08 to 0.72
AB loaded	0.23	0.48	–1.36 to 0.59
ER+AB loaded	0.42	0.56	–0.01 to 0.85
DF loaded	0.28	0.35	–0.05 to 0.61
ATiFL sectioned (n=4)			
N	0.00	0.18	–0.29 to 0.29
N loaded	0.05	0.62	–0.05 to 0.15
ER	–0.03	0.16	–0.28 to 0.23
ER loaded	0.09	0.27	–0.34 to 0.52
AB loaded	–0.14	0.17	–0.41 to 0.14
ER+AB loaded	–0.05	0.15	–0.29 to 0.18
DF loaded	0.11	0.18	–0.18 to 0.40
AD sectioned (n=3)			
N	0.05	0.18	–0.40 to 0.49
N loaded	0.52	0.23	–0.04 to 1.09
ER	0.27	0.40	–0.73 to 1.26
ER loaded	0.65	0.68	–1.04 to 2.34
AB loaded	1.19	0.79	–0.78 to 3.10
ER+AB loaded	1.45	1.04	–1.13 to 4.02
DF loaded	0.66	0.41	–0.35 to 1.67
PTiFL sectioned (n=2)			
N	0.07	0.15	–1.28 to 1.42
N loaded	–0.58	0.18	–4.79 to 4.53
ER	0.02	0.15	–1.34 to 1.39
ER loaded	–0.19	0.69	–6.41 to 6.04
AB loaded	–0.17	0.34	–3.26 to 2.92
ER+AB loaded	0.05	–	–
DF loaded	–0.06	0.46	–4.19 to 4.06
ATiFL and AD sectioned (n=5)			
N	–0.04	0.18	–0.26 to 0.18
N loaded	–0.68	0.60	–0.12 to 0.76
ER	0.06	0.17	–0.16 to 0.27
ER loaded	0.58	0.57	–0.18 to 1.29
AB loaded	0.87	0.97	–0.34 to 2.07
ER+AB loaded	0.98	1.01	–0.27 to 2.32
DF loaded	0.41	0.41	–0.09 to 0.92
ATiFL and PTiFL sectioned (n=5)			
N	–0.03	0.13	–0.18 to 0.13
N loaded	–0.16	0.73	–0.37 to 1.02
ER	0.09	0.23	–0.19 to 0.38
ER loaded	0.33	0.16	0.13 to 0.53
AB loaded	0.43	0.54	–0.62 to 0.71
ER+AB loaded	0.21	0.43	–0.48 to 0.90
DF loaded	0.00	0.14	–0.18 to 0.18
ATiFL, AD and PTiFL sectioned (n=10)			
N	0.01	0.20	–0.13 to 0.16
N loaded	–0.43	0.64	0.01 to 0.63
ER	0.01	0.19	–0.12 to 0.15
ER loaded	0.37	0.36	0.11 to 0.62
AB loaded	0.50	0.90	–0.14 to 1.14
ER+AB loaded	0.75	0.97	0.00 to 1.49
DF loaded	0.20	0.32	–0.30 to 0.43

See Table 1 for abbreviations.

Table 4. Translation Z: Posterior–anterior displacement of the fibula relative to the tibia after transection of the tibiofibular and deltoid ligaments in different positions and loading conditions (mean and SD; relative to the intact neutral unloaded situation). Negative value = posterior displacement

	Translation Z		
	Mean	SD	95% CI
Intact (n=10)			
N	–	–	
N loaded	0.13	0.89	–0.56 to 0.81
ER	–0.92	1.01	–1.64 to –0.20
ER loaded	–0.92	1.01	–1.69 to 0.15
AB loaded	0.58	0.64	0.09 to 1.07
ER+AB loaded	–0.74	0.98	–1.51 to 0.02
DF loaded	–0.62	0.54	–1.12 to –0.11
ATiFL sectioned (n=4)			
N	–0.31	0.57	–1.21 to 0.59
N loaded	0.02	0.24	–0.36 to 0.40
ER	–0.91	0.39	–1.53 to –0.29
ER loaded	–1.36	1.07	–3.07 to 0.35
AB loaded	0.37	0.34	–1.18 to 0.91
ER+AB loaded	–0.67	0.50	–1.47 to 0.13
DF loaded	–0.33	0.53	–1.17 to 0.52
AD sectioned (n=3)			
N	–0.27	0.99	–2.73 to 2.20
N loaded	–0.57	0.63	–2.53 to 3.45
ER	–1.72	1.32	–5.01 to 1.57
ER loaded	–0.85	1.17	–3.74 to 2.05
AB loaded	1.14	0.30	0.41 to 1.88
ER+AB loaded	0.01	0.99	–2.46 to 2.47
DF loaded	–0.38	0.75	–2.24 to 1.48
PTiFL sectioned (n=2)			
N	–0.42	0.56	–5.42 to 4.59
N loaded	–0.10	0.82	–7.52 to 7.31
ER	0.26	1.04	–9.05 to 9.57
ER loaded	0.14	1.91	–17.0 to 17.3
AB loaded	0.42	1.59	–13.9 to 14.7
ER+AB loaded	–0.23	–	– –
DF loaded	–0.53	0.90	–8.64 to 7.58
ATiFL and AD sectioned (n=5)			
N	–0.93	0.96	–2.12 to 0.26
N loaded	0.62	0.83	–0.41 to 1.65
ER	–1.88	1.22	–3.40 to –0.37
ER loaded	–1.55	1.23	–3.08 to –0.02
AB loaded	–0.35	1.43	–2.13 to 1.43
ER+AB loaded	–1.22	1.54	–3.14 to 0.69
DF loaded	–0.35	0.62	–1.12 to 0.41
ATiFL and PTiFL sectioned (n=5)			
N	0.10	0.68	–0.74 to 0.94
N loaded	–0.19	0.69	–1.28 to 0.90
ER	–0.43	1.62	–2.44 to 1.58
ER loaded	–0.72	2.18	–3.42 to 1.99
AB loaded	0.59	0.69	–0.80 to 0.92
ER+AB loaded	–1.23	0.85	–2.59 to 0.13
DF loaded	–0.50	0.99	–1.73 to 0.73
ATiFL, AD and PTiFL sectioned (n=10)			
N	–0.12	1.12	–0.92 to 0.68
N loaded	0.23	0.78	–0.33 to 0.79
ER	–0.88	1.63	–2.05 to 0.29
ER loaded	–1.03	1.73	–2.27 to 0.21
AB loaded	0.38	0.82	–0.20 to 0.97
ER+AB loaded	–0.85	1.06	–1.66 to –0.03
DF loaded	–0.43	1.12	–1.22 to 0.37

See Table 1 for abbreviations.

Table 5. Rotation X: Rotation of the fibula about the x–axis relative to the tibia after transection of the tibiofibular and deltoid ligaments in different positions and loading conditions (mean and SD; relative to the intact neutral unloaded situation). Negative value = dorsiflexion

	Rotation X		
	Mean	SD	95% CI
Intact (n=10)			
N	–	–	– –
N loaded	0.48	0.35	–0.22 to 0.32
ER	0.35	0.47	0.01 to 0.69
ER loaded	0.36	0.40	0.05 to 0.66
AB loaded	–0.33	0.33	–0.59 to –0.08
ER+AB loaded	0.03	0.30	–0.20 to 0.26
DF loaded	0.06	0.29	–0.21 to 0.32
ATiFL sectioned (n=4)			
N	0.35	0.39	–0.28 to 0.97
N loaded	0.52	0.23	–0.32 to 0.42
ER	0.73	0.34	0.18 to 1.27
ER loaded	0.92	0.66	–0.14 to 1.97
AB loaded	–0.20	0.34	–0.74 to 0.36
ER+AB loaded	0.21	0.55	–0.66 to 1.09
DF loaded	0.29	0.12	0.10 to 0.49
AD sectioned (n=3)			
N	0.08	0.19	–0.40 to 0.55
N loaded	0.01	0.31	–0.75 to 0.77
ER	0.61	0.41	–0.42 to 1.64
ER loaded	0.33	0.52	–0.97 to 1.63
AB loaded	–0.49	0.33	–1.32 to 0.34
ER+AB loaded	–0.12	0.13	–0.45 to 0.21
DF loaded	–0.59	0.14	–0.40 to 0.28
PTiFL sectioned (n=2)			
N	0.04	0.13	–1.14 to 1.21
N loaded	0.03	0.07	–0.58 to 0.63
ER	–0.17	0.46	–4.28 to 3.94
ER loaded	–0.18	0.48	–4.49 to 4.12
AB loaded	–0.53	0.60	–5.46 to 5.35
ER+AB loaded	–0.10	–	– –
DF loaded	–0.03	0.01	–0.11 to 0.05
ATiFL and AD sectioned (n=5)			
N	0.49	0.24	0.19 to 0.79
N loaded	0.05	0.27	–0.29 to 0.38
ER	0.89	0.53	0.23 to 1.54
ER loaded	0.72	0.50	0.10 to 1.33
AB loaded	–0.6	0.45	–0.63 to 0.50
ER+AB loaded	0.27	0.72	–0.63 to 1.17
DF loaded	0.28	0.16	0.07 to 0.48
ATiFL and PTiFL sectioned (n=5)			
N	0.27	0.69	–0.59 to 1.14
N loaded	–0.14	0.05	–0.22 to –0.53
ER	0.16	1.00	–1.08 to 1.40
ER loaded	0.33	1.38	–1.39 to 2.04
AB loaded	–0.28	0.32	–0.68 to 0.12
ER+AB loaded	0.08	0.88	–1.32 to 1.47
DF loaded	0.09	0.67	–0.74 to 0.92
ATiFL, AD and PTiFL sectioned (n=10)			
N	0.31	0.33	0.07 to 0.54
N loaded	–0.08	0.04	–0.39 to 0.24
ER	–0.88	1.63	–0.79 to 1.05
ER loaded	0.58	1.13	–0.23 to 1.38
AB loaded	–0.22	0.38	–0.50 to 0.05
ER+AB loaded	0.24	0.70	–0.29 to 0.78
DF loaded	0.27	0.56	–0.13 to 0.67

See Table 1 for abbreviations.

Table 6. Rotation Y: Rotation of the fibula about the y–axis relative to the tibia after transection of the tibiofibular and deltoid ligaments in different positions and loading conditions (mean and SD; relative to the intact neutral unloaded situation). Negative value = external rotation

	Rotation X		
	Mean	SD	95% CI
Intact (n=10)			
N	–	–	– –
N loaded	–0.27	1.18	–1.18 to 0.64
ER	–2.50	1.38	–3.49 to –1.51
ER loaded	–2.29	1.28	–3.27 to –1.30
AB loaded	–0.26	1.69	–1.56 to 1.04
ER+AB loaded	–1.60	1.30	–2.60 to –0.60
DF loaded	0.57	3.05	–2.25 to 3.39
ATiFL sectioned (n=4)			
N	–1.54	1.46	–3.86 to 0.76
N loaded	–0.63	0.76	–1.83 to 0.58
ER	–3.66	0.76	–4.88 to –2.45
ER loaded	–3.69	1.97	–6.83 to –0.55
AB loaded	–1.10	0.67	–2.16 to –0.04
ER+AB loaded	–2.50	0.93	–3.98 to –1.03
DF loaded	–1.21	1.28	–3.25 to 0.82
AD sectioned (n=3)			
N	0.28	2.83	–6.74 to 7.30
N loaded	–0.08	2.18	–5.50 to 5.35
ER	–0.73	2.16	–6.11 to 4.64
ER loaded	–1.49	2.66	–8.09 to 5.10
AB loaded	0.89	1.34	–2.43 to 4.21
ER+AB loaded	–0.37	2.56	–6.73 to 5.99
DF loaded	–0.40	3.19	–8.33 to 7.52
PTiFL sectioned (n=2)			
N	0.11	0.26	–2.20 to 2.42
N loaded	0.64	0.34	–2.41 to 3.69
ER	–1.38	1.82	–17.7 to 15.0
ER loaded	–1.40	1.52	–15.1 to 12.3
AB loaded	0.12	1.54	–13.7 to 14.0
ER+AB loaded	0.11	–	–
DF loaded	0.38	0.64	–5.40 to 6.16
ATiFL and AD sectioned (n=5)			
N	–1.72	2.14	–4.37 to 0.94
N loaded	–0.61	2.14	–3.27 to 2.05
ER	–3.00	2.35	–5.93 to –0.08
ER loaded	–2.77	2.81	–6.26 to 0.73
AB loaded	–1.60	3.15	–5.52 to 2.31
ER+AB loaded	–2.50	3.14	–6.41 to 1.40
DF loaded	–0.41	1.97	–2.86 to 2.04
ATiFL and PTiFL sectioned (n=5)			
N	–0.20	0.73	–1.10 to 0.70
N loaded	0.15	0.74	–1.03 to 1.32
ER	–3.67	2.37	–6.61 to –0.74
ER loaded	–4.44	3.97	–9.38 to 0.49
AB loaded	–0.15	1.66	–2.21 to 1.92
ER+AB loaded	–2.25	1.80	–5.11 to 0.61
DF loaded	–1.43	1.54	–3.35 to 0.49
ATiFL, AD and PTiFL sectioned (n=10)			
N	–1.65	1.88	–3.00 to –0.30
N loaded	–1.03	2.07	–2.51 to 0.45
ER	–3.03	2.30	–4.67 to –1.40
ER loaded	–4.05	3.71	–6.71 to –1.39
AB loaded	–0.69	2.00	–2.12 to 0.74
ER+AB loaded	–2.60	2.22	–4.31 to –0.90
DF loaded	–1.70	2.10	–3.20 to –0.20

See Table 1 for abbreviations.

Table 7. Rotation Z: Rotation of the fibula about the z–axis to the tibia after transection of the tibiofibular and deltoid ligaments in different positions and loading conditions (mean and SD; relative to the intact neutral unloaded situation). Negative value = abduction

	Rotation Z		
	Mean	SD	95% CI
Intact (n=10)			
N	–	–	–
N loaded	–0.11	0.36	–0.38 to 0.17
ER	0.50	0.26	0.32 to 0.69
ER loaded	0.20	0.35	–0.07 to 0.47
AB loaded	0.25	0.24	–0.16 to 0.21
ER+AB loaded	0.07	0.21	–0.09 to 0.24
DF loaded	–0.30	0.56	–0.81 to 0.21
ATiFL sectioned (n=4)			
N	–0.02	0.17	–0.29 to 0.26
N loaded	–0.24	0.28	–0.69 to 0.22
ER	0.34	0.44	–0.36 to 1.05
ER loaded	0.11	0.47	–0.65 to 0.86
AB loaded	0.11	0.40	–0.52 to 0.73
ER+AB loaded	0.08	0.30	–0.40 to 0.55
DF loaded	–0.12	0.49	–0.90 to 0.65
AD sectioned (n=3)			
N	0.08	0.20	–0.42 to 0.59
N loaded	–0.38	0.50	–1.63 to 0.87
ER	0.02	0.69	–1.68 to 1.74
ER loaded	0.00	0.25	–0.62 to 0.62
AB loaded	–0.27	0.71	–0.45 to –0.09
ER+AB loaded	–0.38	0.12	–0.67 to –0.08
DF loaded	–0.46	0.62	–1.20 to 1.09
PTiFL sectioned (n=2)			
N	–0.12	0.18	–1.77 to 1.54
N loaded	–0.19	0.12	–1.26 to 0.89
ER	0.28	0.42	–3.51 to 4.06
ER loaded	0.25	0.36	–3.02 to 3.52
AB loaded	–0.10	0.20	–1.93 to 1.74
ER+AB loaded	–0.29	–	– –
DF loaded	–0.19	0.38	–3.62 to 3.24
ATiFL and AD sectioned (n=5)			
N	–0.00	0.20	–0.26 to 0.25
N loaded	–0.44	0.47	–1.03 to 0.14
ER	0.42	0.22	0.15 to 0.70
ER loaded	–0.28	0.44	–0.83 to 0.27
AB loaded	–0.25	0.28	–0.60 to 0.10
ER+AB loaded	–0.20	0.17	–0.41 to 0.02
DF loaded	–0.52	0.54	–1.19 to 0.15
ATiFL and PTiFL sectioned (n=5)			
N	–0.09	0.28	–0.44 to 0.25
N loaded	–0.42	0.33	–0.94 to 0.11
ER	0.41	0.16	0.22 to 0.61
ER loaded	0.32	0.30	–0.05 to 0.69
AB loaded	–0.26	0.43	–0.80 to 0.28
ER+AB loaded	0.01	0.35	–0.55 to 0.56
DF loaded	0.00	0.25	–0.31 to 0.32
ATiFL, AD and PTiFL sectioned (n=10)			
N	–0.06	0.21	–0.22 to 0.09
N loaded	–0.38	0.28	–0.58 to –0.18
ER	0.25	0.25	0.07 to 0.43
ER loaded	0.09	0.46	–0.24 to 0.42
AB loaded	–0.31	0.22	–0.47 to –0.15
ER+AB loaded	–0.14	0.28	–0.35 to 0.07
DF loaded	–0.26	0.39	–0.54 to 0.02

See Table 1 for abbreviations.

Positions

Neutral and loaded neutral. All conditions of N, except P, resulted in a posterior translation that largely disappeared when loaded. A resulted in 1.5° external rotation. This slightly increased with A+D and A+D+P, and decreased in N–L. N–L gave a lateral translation that was largest after A+D. Under some conditions, N–L resulted in a caudal displacement.

Loaded dorsiflexion. Of all positions, DF–L caused the largest increase in tibiofibular width under any condition, as well as a tendency of cranial and posterior translation in most conditions. Rotations showed a large variety of results.

Loaded abduction. AB–L resulted in an increase in tibiofibular width under any condition. With the exception of A+D, posterior translation was seen under all conditions also. Rotations about the x–axis were mainly negative, but the other rotations showed wide variability.

Loaded external rotation–abduction. Conditions during ER+AB–L showed a tendency to lateral (except A+P) and posterior (except D) translation, as well as a relatively large external rotation (except P). Adduction resulted from conditions that included P.

External rotation and loaded external rotation. ER and some conditions of ER–L resulted in a medial translation of the fibula. All conditions except PS resulted in posterior translation and external rotation.

Discussion

By using a standard scheme, we inserted the markers in a similar pattern in all legs. Without this help, it would have been difficult to obtain an appropriate marker distribution in the fibula. Because of its small diameter, the markers cannot always be distributed far enough from the fibular central axis in this bone. The translations we have shown are translations of the geometric center of the markers. Because we had similar patterns of markers, the effect of marker scatter on the value of the translations cannot have been large. The main influence of the scatter on the translation results was caused by other factors, such as differences in leg geometry.

For all parameters tested, there was generally a very large dispersion around the median value, indicating a low reproducibility between the cadavers or specimens. Thus, we have only highlighted the results that were consistent, which means that a certain transection condition or position always resulted in the same kind of displacement. It is of interest that in the neutral situation, displacements were found after sectioning the ligaments. This is probably because the connection between tibia and fibula at the level of the distal tibiofibular syndesmosis in the horizontal plane may be considered to be a ring (anterior tibiofibular ligament, fibula, posterior tibiofibular ligament, tibia, anterior tibiofibular ligament). In every ring there is a certain rest–tension. When the ring is disrupted at one level, for example at the anterior tibiofibular ligament, the rest tension cannot be maintained and there will be a relaxation in the other structures involved, in this case the posterior tibiofibular ligament. Thus transection of one ligament will result in a displacement. Depending on the position of the leg, this may be influenced further by other forces such as gravity and the testing procedure.

We found the largest and most consistent fibular displacements at the distal syndesmosis during ER of the ankle–foot complex. This is in accordance with the general clinical knowledge that ER is the most important of the mechanisms known to injure the syndesmosis, reflected by the numerous reports that have used external rotation in the assessment of syndesmotic injuries (Lauge–Hansen 1950, Kelikian and Kelikian 1985, Boytim et al. 1991, Xenos et al. 1995, Hahn and Colton 2000, Beumer et al. 2003).

In this study, ER resulted in a rotation of the fibula that ranged between 1.2º of internal rotation and 7.7º of external rotation under all sectioning conditions. This correlates well with the 1.5–8º "negative lateral tibial rotation at the syndesmosis" (external rotation of the fibula) that Close (1956) described by measuring the angle between Steinmann pins placed in the tibia and fibula. In the intact situation, he found between 1.5º and 2.5º of external rotation in 3 specimens. After sectioning of the ATiFL, rotation increased to 2.5–4.5º, which further increased to 4–6.5º after IL had been sectioned, with a maximum of 8º of external rotation after ATiFL, IL and PTiFL had been sectioned. These values are similar to the values we found

after unloaded ER, where IL was left intact. This may suggest that additional IL sectioning might not increase external rotation of the fibula.

ER resulted in a reduction in tibiofibular width. This explains why anterior syndesmotic instability cannot be seen on anterior–posterior ankle radiographs. Unloaded ER of the intact ankle resulted in posterior translation ranging from –1.1–2.6 mm, which decreased to –1.5–1.7 mm with 750 N axial load applied. This is an accurate measurement of the posterior translation of the fibula that was found and reported without giving numeric values by Xenos et al. (1995) and Close (1956), after application of an external rotation force to the talus. It is also a quantification of displacements occurring during the "external rotation stress test" that may be performed after osteosynthesis of malleolar fractures (Hahn and Colton 2000). A previous study, however, showed that this posterior translation cannot be recognized on lateral ankle radiographs due to external rotation of fibula and tibia during the external rotation stress examination (Beumer et al. 2003). Finally, it seems evident that this posterior translation during ER of the ankle provides an additional stress to the ATiFL that is already tensioned due to external rotation of the fibula. This could explain why ATiFL injuries are more common than PTiFL injuries, and how ATiFL injuries can occur without other ankle injuries.

Clinical relevance

Guidelines for the treatment of acute ligamentous syndesmotic injuries may be formulated based on the current literature and extrapolations from this study. These guidelines can only be used when no other injuries around the ankle are present.

Fibular displacements after sectioning of the ATiFL

Mechanical instability of the syndesmosis was found after isolated sectioning of the ATiFL, by applying ER or ER–L. This is in accordance with the "open book" type of injury that has been described by Kelikian and Kelikian (1985).

Displacements in N and N–L did not exceed the intact situation. This implies that the ATiFL may heal within acceptable limits if the ankle is kept in the neutral position. This can probably be achieved by a snugly fitted below–knee plaster. Although no reports can be found on this particular topic, by analogy with tibial shaft fractures, we assume that this plaster will prevent external rotation of the ankle (Zagorski et al. 1993).

The amount of external rotation of the fibula after isolated sectioning of the ATiFL varied between specimens, indicating that this may vary between patients as well. In the case of suspected acute ATiFL injury, we recommend MR imaging—preferably with an additional oblique axial plane (Takoa et al. 2003, Beumer et al. 2005a) to assess the status of the ligament, and application of a plaster when a complete rupture is found. When MR imaging has excluded injuries to other structures, such as the interosseous ligament and membrane, the patient may bear weight because displacements in the neutral loaded position did not increase much after loading. If treatment is based on the clinical picture without MR imaging having been performed in the first week after the injury, the patient should be advised not to bear weight.

Fibular displacements after sectioning of AD

This sectioning condition was included in our study to assess whether isolated rupture of the deltoid ligament (such as in the stage–1 pronation–external rotation injury described by Lauge–Hansen (1950) would result in syndesmotic instability. Increased tibiofibular width and increased vertical fibular translation of the fibula were seen in most positions. However, this never exceeded displacements found in the intact situation. Thus, a functional treatment of isolated ruptures of AD seems justified.

Fibular displacements after sectioning of the ATiFL and AD

As with A or D, displacements in the neutral situation did not exceed values found in the intact situation. When compared to the condition when only the ATiFL was sectioned, displacements after A+D showed an increase in tibiofibular width during loading in nearly all positions (the largest being 2.32 mm). After A+D, the largest displacements in the neutral position did not exceed the values found when the ankle was put in DF, ER, AB and ER+AB in the intact situation. This indicates that the ATiFL and AD may heal within physiological

limits after A+D, if the ankle is kept in the neutral position. We recommend that patients with these injuries be treated in the same way as those with isolated ATiFL injuries.

Fibular displacement after isolated sectioning of the PTiFL

Although we have never encountered isolated injuries of the PTiFL, we chose to include this sectioning condition for reasons of completeness. Since posterior ankle arthroscopy and shaving procedures in the area of the TL and PTiFL become more frequent, iatrogenic isolated PTiFL injuries may be the result. A wide variety of displacements was seen after P. The most interesting and largest displacements found were 1.6 mm anterior translation and 2.7° of external rotation of the fibula during some of the trauma mechanisms. As these displacements did not exceed those in the neutral situation, a functional treatment of isolated ruptures of the PTiFL may be justified.

Fibular displacements after sectioning of ATiFL–PTiFL or ATiFL–AD–PTiFL

Very little displacement was seen after A+P and A+D+P in the neutral (unloaded or loaded) situation with regard to tibiofibular width. This may be related to the fact that the interosseous membrane and ligament were not transected. The integrity of IL probably has no influence on fibular external rotation. Indeed, a large increase in external rotation of the fibula was found after ER of the ankle–foot complex in both the unloaded and loaded situation. Those displacements were greater than during ER in the intact situation; thus, it is clear that patients with such injuries cannot be treated functionally. In the clinical situation, combined injury of ATiFL–PTiFL or ATiFL–AD–PTiFL will be accompanied by IL injury (Lauge–Hansen 1950, Mullins and Sallis 1958, Kelikian and Kelikian 1985) and result in such diastasis and instability that surgical treatment such as placement of a syndesmotic screw (instead of plaster immobilization) is warranted. We have recently shown that with 750 N axial load on a lower leg, a syndesmotic screw to stabilize extensive syndesmotic injury will result in syndesmotic widening beyond its normal range (Beumer et al. 2005b). Based on the current literature and extrapolations from the present study, we recommend that patients with combined injury of ATiFL–PTiFL or ATiFL–AD–PTiFL should be treated with a syndesmotic screw and that they should not bear weight.

Contributions of authors

AB and BAS designed and performed the study, interpreted the results, and wrote the manuscript. ERV and EHG analyzed and interpreted the RSA examinations. RN designed and constructed the testing apparatus. AZG facilitated the radiological laboratory work. JR performed the overall statistical analysis.

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American Academy of Orthopaedic Surgeons. Joint motion. Method of measuring and recording. Churchill Livingstone, Edinburgh, 1965.

Beumer A, Valstar E R, Garling E H, Van Leeuwen W J, Sikma W, Niesing R, Ranstam J, Swierstra B A. External rotation stress imaging in syndesmotic injuries of the ankle. Lateral radiography and radiostereometry compared in a cadaveric model. Acta Orthop Scand 2003; 74: 201–5.

Beumer A, Hermans J J, Niesten D D, Heijboer M P. Late reconstruction of the anterior tibiofibular syndesmosis for ankle diastasis with talar shift in a 12–year–old boy. A case report. Foot Ankle Surg 2005a; 11: 49–53.

Beumer A, Campo M M, Niesing R, Day J, Kleinrensink G J, Swierstra B A. Screw fixation of the syndesmosis. A cadaver model comparing stainless steel and titanium screws and 3 and 4 cortical fixation. Injury 2005b; 36: 60–4.

Börlin N, Thien T, Kärrholm J The precision of radiostereometric measurements. Manual vs. digital measurements. J Biomechanics 2002; 35: 69–79.

Boytim M J, Fischer D A, Neumann L. Syndesmotic ankle sprains. Am J Sports Med 1991; 19: 294–8.

Close R. Some Applications of the Functional Anatomy of the Ankle joint. J Bone Joint Surg (Am) 1956; 38: 761–82.

Colville M R, Marder R A, Boyle J J, Zarins B. Strain measurement in lateral ankle ligaments. Am J Sports Med 1990; 18: 196–200.

Frick H. Zur Entstehung, Klinik, Diagnostik und Therapie der isolierten Verletzung der tibiofibularen Syndesmose. Unfallheilkunde 1978; 81: 542–5.

Grath G B. Widening of the ankle mortise. Acta Chir Scand (Suppl) 1960; 263.

Hahn D M, Colton C L. Malleolar fractures. In: Rüedi T P and Murphy W L. AO Principles of Fracture Management. Thieme, New York, Stuttgart 2000: 559–81.

Kelikian H, Kelikian A. Disorders of the ankle. W.B. Saunders Company, Philadelphia/London/Toronto 1985.

Lauge–Hansen N. Fractures of the ankle 2. Combined experimental–surgical and experimental–roentgenologic investigations. Arch Surg 1950; 60: 957–85.

Miller C D, Shelton W R, Barrett G R, Savoie F H, Dukes A D. Deltoid and syndesmosis ligament injury of the ankle without fracture. Am J Sports Med 1995; 23: 746–50.

Mullins J, Sallis J. Recurrent sprain of the ankle joint with diastasis. J Bone Joint Surg (Br) 1958; 40: 270–3.

Pankovich A M. Fractures of the fibula at the distal tibiofibular syndesmosis. Clin Orthop 1979; (143): 138–47.

Rasmussen O, Tovborg–Jensen I, Boe S. Distal tibiofibular ligaments. Analysis of function. Acta Orthop Scand 1982; 53: 681–6.

Söderkvist I, Wedin P. Determining the movements of the skeleton using well–configured markers. J Biomechanics 1993; 26 (12): 1473–7.

Takao M, Ochi M, Oae K, Naito K, Uchio Y. Diagnosis of a tear of the tibiofibular syndesmosis. The role of arthroscopy of the ankle. J Bone Joint Surg (Br) 2003; 85: 324-9.

Valstar E R, Vrooman H A, Toksvig–Larsen S, Ryd L, Nelissen R G H H. Digital automated RSA compared to manually operated RSA. Journal of Biomechanics 2000; 33: 1593–9.

Weber B. Die Verletzungen des oberen Sprunggelenkes, 2 Aufl Huber, Bern Stuttgart, Wien 1966.

Xenos J S, Hopkinson W J, Mulligan M E, Olson E J, Popovic N A. The tibiofibular syndesmosis. Evaluation of the ligamentous structures, methods of fixation, and radiographic assessment. J Bone Joint Surg (Am) 1995; 77: 847–56.

Zagorski J I, Latta L L, Finnieston A R, Zych G. Tibial fracture stability. Analysis of external fracture immobilization in anatomic specimens in casts and braces. Clin Orthop 1993; (291): 196–207.