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REVIEW ARTICLE

Chronic ankle instability: Biomechanics and pathomechanics of ligaments injury and associated lesions

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Summary The objective of this study was to evaluate the conditions of ankle stability and the morphological and/or lesional factors in sprains that determine when instability becomes chronic. It is based on a review of the literature and the data from the 2008 Sofcot symposium. The biomechanics of the ankle cannot be reduced to a simple flexion—extension movement with one degree of freedom as characterized by the talocrural joint: its function cannot be dissociated from the subtalar joint, allowing the foot to adapt to the ground surface. Functional stability is related to the combination of the particular biometry of the joint surfaces and a multiaxial ligament system. The bone morphology of the talus, shaped like a truncated cone, explains the potential instability in plantar flexion; the radii of curvature of the talar dome have a variable mediolateral distribution: most often the medial radius of curvature is inferior to the lateral radius of curvature (66%), sometimes equal (19%), or inverted (15%). Joint kinematics, combining rotation and slide, can therefore be modulated by the talar morphology, explaining the occurrence of at-risk ankles. Ligament stability relies on the organization in three parts of the lateral collateral ligament and the specific subtalar ligaments: the cervical and the talocalcaneal interosseous ligament. The different injury mechanisms are largely responsible for the sequence of ligament lesions: the most frequent is inversion. The first ligament stabilizers correspond to the cervical and anterior talofibular ligaments; the talocalcaneal ligament, by its oblique orientation, is solicited when there is a dorsal varus-flexion component. In chronic instability, these mechanisms explain the onset of associated lesions (impingement, osteochondral lesions, fibular tendon pathology), which can play a role in instability syndrome. Ligament

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lesions determine laxity, characteristic of mechanical instability. Functional instability goes along with proprioceptive deficiency. There are postural factors such as varus of the hindfoot that favor instability. Knowledge of all these factors, often associated, will provide a precise lesional assessment and treatment adapted to the instability.
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Introduction

Understanding ankle instabilities remains difficult because of their complexity, which is related to the interference of a large number of parameters. The risk factors of developing chronic instability have been classified into intrinsic and extrinsic factors. Briefly, the intrinsic factors group individual data, essentially morphological, with their variations (bone, ligament, and posture) and the extrinsic factors with environmental data (injury mechanism occurring in sports and/or professional contexts). The interrelation of these different factors, now better studied [1—6], can explain the passage to chronic instability syndrome. Based on our work and the data reported in the literature, we will analyze these different factors, the knowledge of which will participate in the choice of complementary examinations to undertake in cases of chronic instability of the ankle and the therapeutic strategies available.

From morphology to biomechanics

The mechanical behavior of the talocrural joint cannot be reduced to a flexion—extension movement with a working axis and one degree of freedom reflecting joint ginglymus. Its mechanical function is to transmit the body weight to the entire foot and to distribute a system of vertical stresses to a horizontal system represented by plantar weightbearing. There is a narrow interdependence between the talocrural joint and the subtalar joint, which are functionally indissociable [7,8], with the subtalar joint having a preferential rotation mobility (trochoid joint) allowing the foot to adapt to the ground. Joint kinematics results from a morphology and a biometric organization of the joint surfaces and a very specific multiaxial ligament system that will be clarified below.

Bone factors

The trochlea of the talus was compared to a truncated cone [9,10] whose mean angle at the summit is 24° (±11°); the rotational axis is oriented along a double obliquity: in the coronal plane, below and laterally passing under the tip of the two malleoli (at an angle of 82 ± 3.6° with the tibia axis) and in the transversal plane, back and laterally at a 20°—30° angle with the transversal axis of the knee. This form makes it impossible to take into account certain anatomic details: a lateral edge that has greater inclination than the medial edge, a wider trochlea in front than behind, and a posterior part of the lateral edge that is beveled and triangular (Fig. 1). The wider anterior part of the space between the malleoli is reduced from front to back, as in the tibiofibular mortise: this difference in width between the anterior edge and the posterior edge varies a mean 4 ± 2 mm [11]. The lateral and medial joint surfaces of the body of the talus fall within circles situated in different sagittal planes and have different and variable radii of curvature. According to anatomic studies by Bonnel, Mabit, and Bedin, conducted for the Sofcot 2008 symposium, the study of radii of curvature has made it possible to individualize three types of talus: for type 1, the medial radius of curvature is smaller than the lateral radius of curvature; for type 2, the medial and lateral radii of curvature are identical; for type 3, the medial radius of curvature is larger than the lateral radius. Bonnel found 86% type 1, 11% type 2, and 3% type 3. In their CT study of 32 tali, Bedin and Mabit reported comparable radius of curvature values, but a different typological distribution: type 1 (21/32 cases; 66%) with a mean medial radius of curvature of 17 mm and a mean lateral radius of 20 mm; type 2 (6/32 cases; 19%) with identical medial and lateral radii (mean, 18.6 mm), and type 3 (5/32 cases; 15%) with a mean 21-mm medial radius of curvature, greater than the mean lateral radius of 19 mm (Fig. 2). In addition, Bonnel demonstrated [12] that there were three radii of curvature falling within circles situated in different spatial planes: the lateral edge of the talar trochlea if made up of two circles situated in two different planes: the first circle called ''lateral malleolar'' parallel to the sagittal plane, and the second called ''lateral talar'' inclined 45° compared to the first. These two circles join at the middle and anterior parts of the lateral edge, separating toward the back to form a triangular space (Fig. 1). This triangular space corresponds to the posterior part of the lateral beveled edge. The medial curvature, called ''medial talar'' presents a rounded edge. The space between the two circles is asymmetrical: the presence of the triangular margin, described above, explains the wider aspect in the front than in the back, slightly curved toward the inside of the talar trochlea. The shape analyzed is complex, but it explains highly important kinematic consequences.

As for the joint kinematics, several movement axes have been described. Based on the determination of the curvature centers of the medial and lateral edges of the trochlea, Barnett et al. [13] and Hicks [14] found two different axes, one axis for plantar flexion oriented obliquely from bottom to top and from medial to lateral, and one axis for dorsal flexion oriented from top to bottom and from medial to lateral. This bone segment allows two types of movement, a purely rotational movement and a rolling movement (rotation plus sliding) (Fig. 3). These two movements can be associated. The rolling phase evolves with instantaneous centers of rotation. In most subjects, instantaneous centers of rotation axes are grouped in a more or less extensive zone projected onto the talus body. For Carret [15], this grouping corresponds to perfect congruence of the joint surfaces, whereas dispersion corresponds to joint dysfunction.

In the sagittal plane, the stability of the talocrural joint is both bone- and ligament-based. During the propulsion phase, the shearing forces are neutralized by the talus

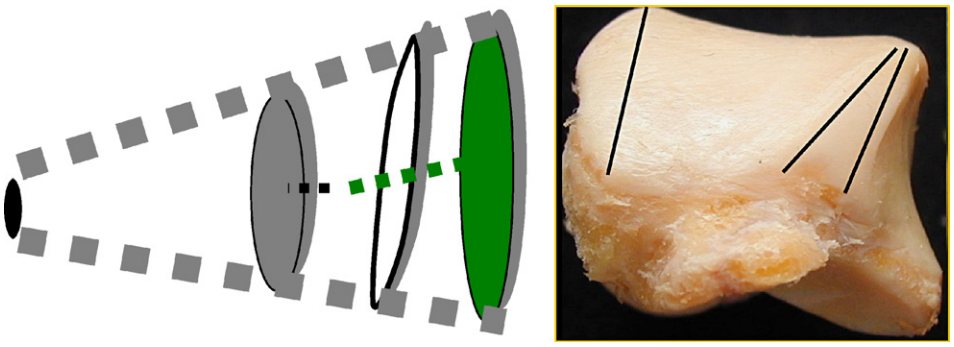


Figure 1 Morphology of the talus: asymmetric truncated cone.

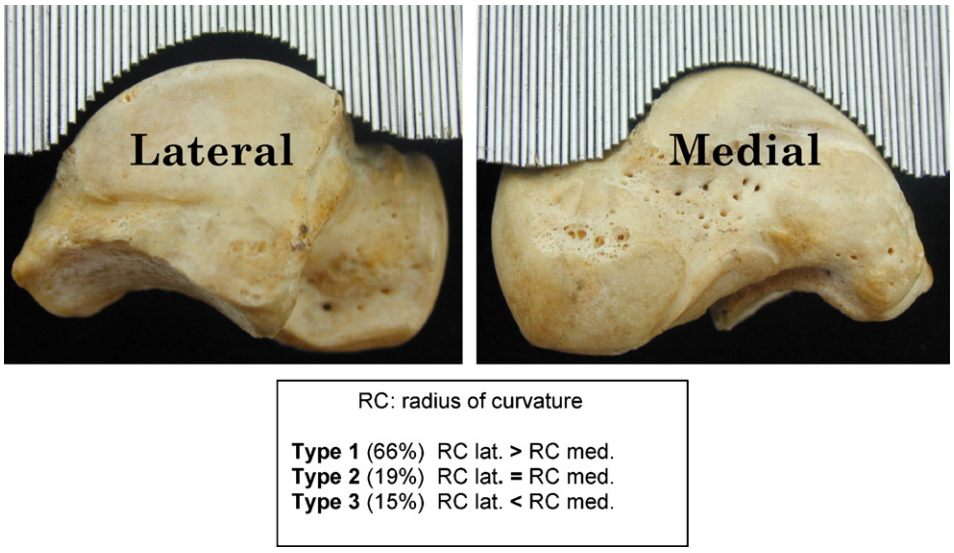


Figure 2 Biometric CT study (32 tali) (Bedin-Mabit).

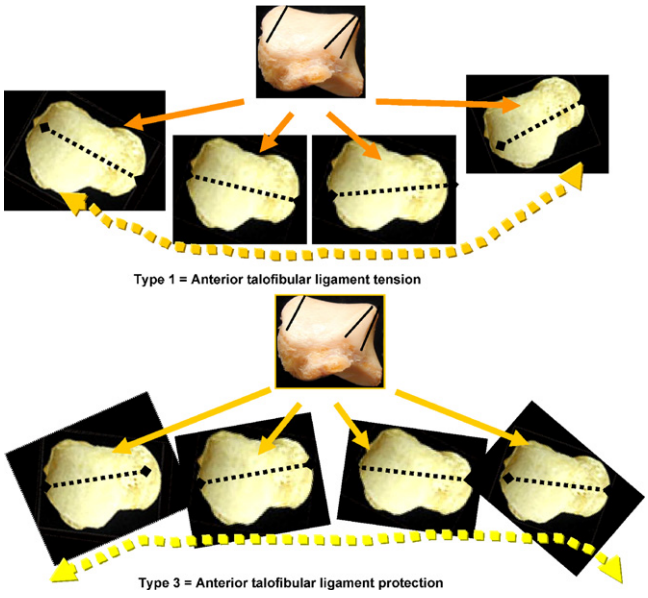


Figure 3 Representation of rolling/sliding kinematics.

embedding into the mortise, with the talus acting as the keystone of the tibiofibular mortise. This mechanism is not the only one in action: the convex—concave aspect of all the joint surfaces and the orientation of the mortise roof surface, which is oblique toward the front by 5°, also come into play.

Ligament factors

The ligament system plays a fundamental role in the ankle's stability and includes a talocrural complex and a subtalar complex that are functionally related. For the talocrural joint, three lateral collateral ligaments are present and one medial collateral ligament.

Lateral collateral ligament (LCL)

This ligament classically comprises three ligaments that insert on the fibula and terminate either on the talus or the calcaneus. The anterior talofibular ligament arises from the anterior edge of the lateral malleolus of the fibula, runs horizontally forward and downward and attaches to the neck of the talus, in front of the lateral malleolar facet. This very short ligament widens slightly from top to bottom. The calcaneofibular ligament, covered by the sheath of fibularis

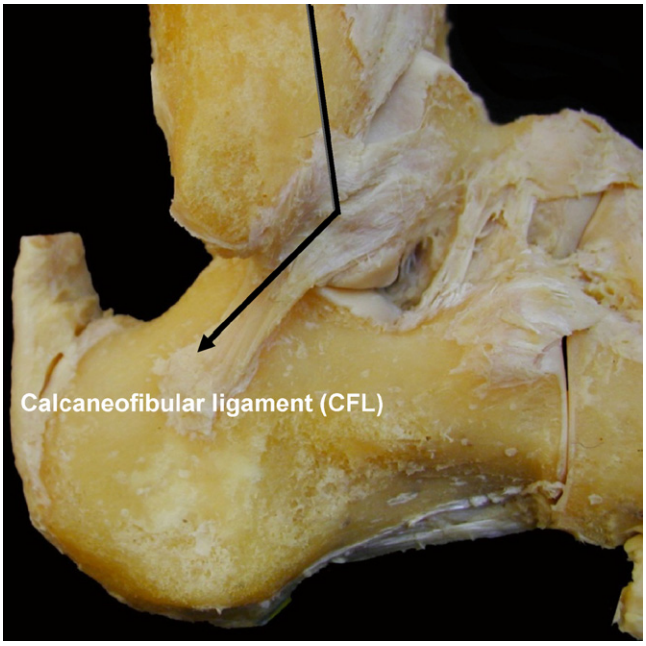


Figure 4 The ligaments of the lateral ligament plane: posterior orientation of CFL.

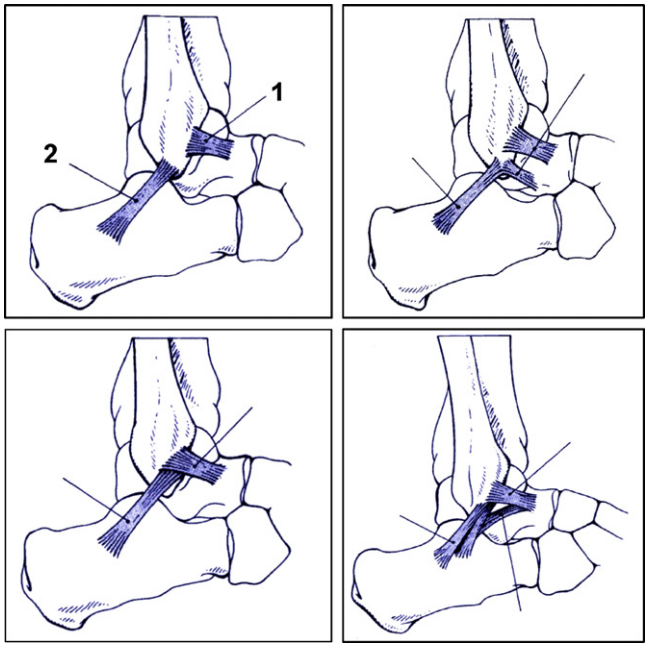


Figure 5 Examples of anatomic variations of the anterior talofibular and (1) and calcaneofibular (2) ligaments [19].

tendons, arises from the summit of the lateral malleolus and attaches below and behind on the lateral side of the calcaneus. Its main characteristic is related to its posterior orientation, along a 45° angle in relation to the lateral malleolus axis [16—18] (Fig. 4). The posterior talofibular ligament, located very deeply and very strong, extends horizontally from the excavation presented at the back by the lateral malleolus to the posterior side of the talus, immediately below the pulley of the talus. Possible morphological variations exist in this ligament arrangement [19]: the anterior ligament can be doubled or there can be an accessory ligament between the anterior and middle ligament (Fig. 5).

Medial collateral ligament (MCL)

The medial deltoid ligament comprises two clearly distinct layers, one superficial and the other deep.

The superficial layer is triangular and corresponds to the deltoid ligament. It arises from the summit of the medial malleolus and then spreads out following its fibers: the posterior tibiotalar part, the strongest, runs down and behind on an insertion tubercle on the medial side of the talus, the tibiocalcaneal part runs vertical to the medial edge of the sustentaculum tali, and the tibionavicular part and anterior tibiotalar part attach to the navicular bone and on the plantar calcaneonavicular (spring) ligament. With the plantar calcaneonavicular ligament, this makes up the anteromedial stabilizer of the peritalar joint, described as the ''coxapedis'' [20].

The deep fibrous and strong layer is made up of bundles extending diagonally from the deep side of the medial malleolus summit to the entire portion of the medial plane of the talus situated below the trochlea and for the ligaments the most anterior part of the talus neck.

Ligaments of the talocalcaneal or subtalar joint

The subtalar joint has its own ligament system. The talus and the calcaneus present two completely distinct joints, one anterior, the other posterior, separated by a groove: the sinus tarsi. The interosseous talocalcaneal ligament occupies this space with vertical and diagonal bands, intermingled with adipose tissue; it is disposed obliquely (approximately 35° compared to the coronal plane) and can be considered the central pivot (equivalent of the cruciate ligaments of the knee) of rotatory stability.

This is completed by collateral ligaments: medial, posterior, and lateral talocalcaneal (inconstant) and most particularly the anterolateral talocalcaneal ligament, which, as described by several authors but often poorly known, corresponds to the cervical ligament: sometimes with a multifasciculated aspect, it joins the neck of the talus to the lateral edge of the calcaneus and is the first anterolateral stabilizer of the subtalar joint. It is laterally interlinked with the extensor retinaculum [21] (Fig. 6).

The fibulocalcaneal ligament, often described as a stabilizer of the subtalar joint, actually intervenes in the stability of the talocalcaneal unit (Fig. 7).

Joint kinematics

Contrary to the principle of pure ginglymus with a working axis and one degree of freedom, the talocrural joint has more complex joint movements. Functionally speaking, the position of maximal stability or joint stabilization (closed packed position) corresponds to the talocrural joint in maximum dorsal flexion and to the subtalar joint at the eversion position with calcaneal valgus: this is obtained in the squatting position or climbing, with maximal joint congruence and the talus embedded in the mortise [7,22]. During walking

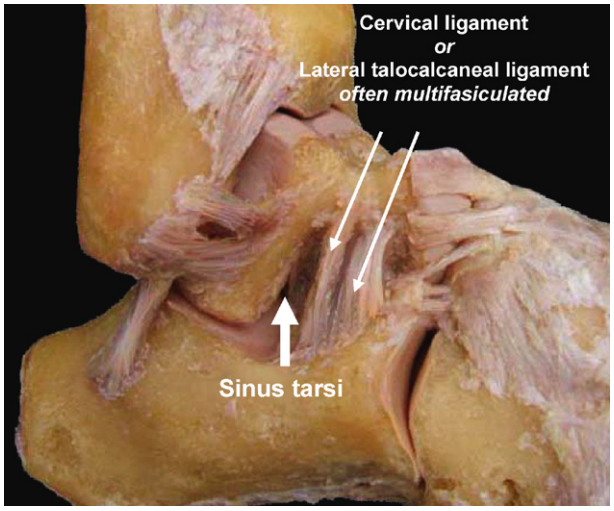


Figure 6 The cervical ligament: anterolateral subtalar lock.

and as soon as plantar flexion has been attained, the ankle appears to be in potential instability.

During a supination movement, there is a first stabilizer at the subtalar joint, which brings into play the cervical ligament (lateral collateral ligament) and when the movement is accentuated, the talocalcaneal interosseous (at least its lateral fibers); if this movement is completed by plantar flexion to achieve inversion, the second stabilizer is made up of the anterior talofibular ligament. This double stabilization is essential and clinically explains the associated (most often) or dissociated impairment of the talocrural and subtalar joints.

During plantar flexion, the talus carries out a medial rotation (in the transversal plane) or an adduction movement, and during dorsal flexion a lateral rotation or abduction movement. The rotational range of motion, which is automatic when passing from plantar flexion to dorsal flexion, is produced for the most part between the neutral position and dorsal flexion. It has been evaluated variably by different authors: from 5° to 6° for Close [9], 12° for Fitzgerald et al. [23], 10° for Parlasca et al. [24], and 18° for Mc Cullough and Burge [25]. When a 50-kg load is applied to the ankle, Lundberg et al. [26] reported a rotational movement of the talus around a vertical axis with no flexion movement associated: with medial rotation of the tibia, the talus made a lateral rotation movement. They considered the talocrural joint as a joint with two degrees of freedom. Although Inman [10] considered talus movements, in the three spatial planes, as the consequence of a rotational movement around a single oblique axis, now most authors [27—32] consider that the talus makes a combined rolling movement (flexion—extension) associated with a sliding (horizontal rotation) movement with an abduction—adduction component in the coronal plane, in a system of multiaxial dynamics.

On a fixed tibia, the talus makes a pronation movement during dorsal flexion and a supination movement during plantar flexion. This combined movement is produced around an anteroposterior axis and a transversal axis. In this context, the role played by the distal tibiofibular syndesmosis may not be a simple adaptive system to the asymmetry of the talus, but rather a shock absorber of the stresses exerted on the talocrural joint protecting the malleolus from the risk of stress fracture.

On a fixed talus, the tibia makes a rotational movement along an anteroposterior axis: during plantar flexion, the tibia makes a lateral rotation movement, and during dorsal flexion, the tibia makes a medial rotational movement. The movement has a variable range of motion whose kinetics depend on the typology of the talar radii of curvature.

In type I, the most frequent, an asymmetrical rolling is produced, following the principle of a cone revolving asymmetrically (marked by the triangle of the talus in the posterolateral position), associating a combined rolling-sliding movement, with the talus acting like a vehicle backing up to park in the mortise. Depending on the direction of dorsal or plantar flexion, the ligament tension predominates on the posterior or anterior component: this is true rotatory stabilization. The middle component (the calcaneofibular ligament), by its oblique orientation toward the back, remains highly variable in its behavior: in approaching a right angle with the anterior talofibular ligament (in dorsiflexion), it stabilizes the talus. The medial ligament of the ankle is the ankle's anchor point and the pivot around which rotational movement is produced.

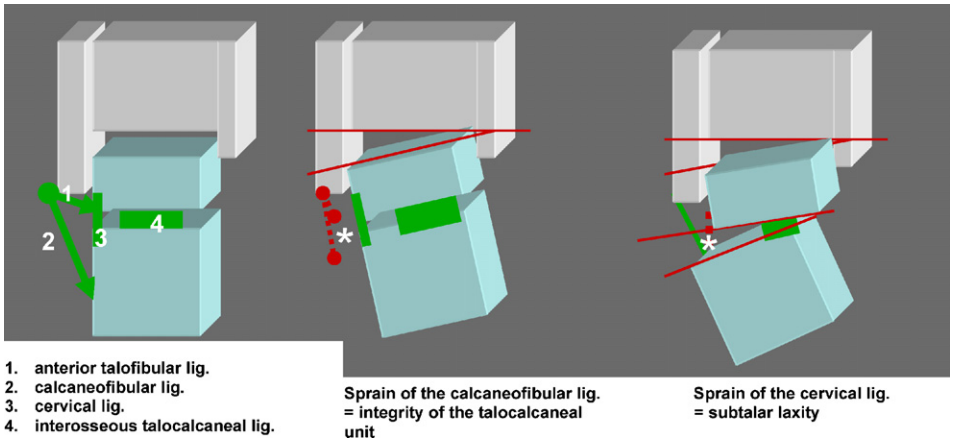


Figure 7 Collateral ligament complex: sprain of the calcaneofibular ligament does not mean subtalar instability.

In type II, in which the radii of curvature are identical, the rotatory stress is lower and therefore the anterior talofibular ligament is solicited.

Type III, where the medial radius of curvature is greater than the lateral radius of curvature, is a true protection morphotype for the anterior talofibular ligament and the cervical ligament, by maximally reducing the medial rotation and supination component.

Osteoligamentous morphology is not the only fundamental aspect of this rotatory stabilization: the periarticular tendon complex plays an important role in functional anticipation of contraction depending on the foot's position. All these tendons (particularly the fibular and posterior tibial tendons) are essential for joint stabilization and adaptive weightbearing function on the ground. The importance of these active stabilizers must be taken into account when considering their use in a tendon transfer aiming to remediate ligament incompetence.

Pathomecanics of ligaments and associated lesions

Injury mechanisms

Of the principle sprain mechanisms, inversion is the most frequent [33—37]: it occurs by catching the lateral edge of the forefoot or a fall on the lateral edge of the forefoot, which first solicits the cervical ligament (lateral talocalcaneal ligament) and the talofibular ligament as well as sometimes the bifurcate ligament in extreme instances of torsion [38—40]. Thus, associated lesions (overstretching) of the sensory nerves (branches of the sural and superficial fibular nerves, participating in capsular innervation) or the fibular tendons can occur. Involvement of the calcaneofibular ligament requires varus with a dorsal flexion component, which is much less common. The rotation is made with the foot blocked on the ground with associated lesions of the medial or lateral compartment depending on the direction of rotation: this mechanism is the source of fibrous impingement and probably certain osteochondral lesions of the talar dome and can also involve tibiofibular syndesmosis. Forced plantar flexion due to catching the forefoot produces lesions of the anterior fibers of the lateral and medial collateral ligaments as well as the anterior capsule, with possible lesions extended to the tarsometatarsal joint. It is therefore essential to search for the injury mechanism for sprains of the talocrural and subtalar joints. However, repeated sprains with sometimes different mechanisms can make this difficult: clinical and imaging examinations to analyze all the ligament structures of the ankle as well as the mid- and hindfoot appear mandatory.

Instability

Two main types of instability can be distinguished: mechanical instability related to anatomic abnormalities of the ankle, usually related to ligament laxity, and functional instability related to posture defects or tendon and muscle adjustment, usually related to a proprioceptive deficit [33,41,42].



Figure 8 Malunion of the fibular malleolus: lateral rotation and diastasis.

Mechanical instability

Bone structure abnormalities of the tibiotarsal complex, ligament laxity, and impairment of range of motion of the tibiotarsal joint related to dorsal flexion deficits are distinguished.

Mechanical bone instability. Other than obvious alterations of the osteochondral cartilage, certain ankle morphotypes favor instability. We have already reported the different morphological varieties of the trochlea and their biomechanical consequences. Unstable ankles can present a congruence defect with a wider talar dome and reduced talar coverage as well as a more anterior position of the talus in relation to the tibia on the lateral X-ray with load [3,43,44]. Several authors [45—48] have studied the position of the lateral malleolus determined based on CT measurements using various indices (the Scranton axial malleolar index or the Lebrun intermalleolar index). In the context of instability, the lateral malleolus seems to be in a posterior position because of distension or rupture of the anterior talofibular ligament, from medial rotation of the talus (notably in pes cavus), or from malunion of the lateral malleolus. On the other hand, the height of the malleolus is not a significant factor influencing stability [44]. Conversely, tibiofibular diastasis caused by a tibiofibular ligament lesion or a malunion of the fibular malleolus (i.e., lateral rotation) is a significant factor to take into account [49] (Fig. 8).

Mechanical ligament instability. Ankle instability does not result only from injury: constitutional hyperlaxity (type Marfan) also exists. The factors making the ankle lax and unstable should be sought. These can be a stimulation defect of the joint mechanoreceptors or, more globally, proprioception dysfunction.

Comparative dynamic X-rays attempt to evaluate this laxity by demonstrating joint subluxation (coronal and sagittal planes), but the value of this type of image remains controversial: muscle fiber contracture can mask underlying laxity [48] and a relation with anatomic variations of ligament ori-

entation may well also be present [7,50]. Subtalar instability is now recognized, but the laxity is difficult to evaluate clinically because of the conformation of this joint. Rotatory instability [51] could find an explanation here. Today MRI provides greater precision on the levels of ligament involvement [21,52].

Mechanical joint instability. The wider talus at the front explains that the deficit in dorsal flexion of the ankle is a factor of instability. Therefore, anterior osteophytosis (impingement exostosis) or anterior synovial hypertrophy (fibrous impingement) are factors aggravating instability and should be integrated into therapy. This limitation in dorsiflexion can also have a functional cause such as retraction of the sural triceps or the gastrocnemial muscles or even a muscle belly extended too far distally. For Barouk et al. [53], short gastrocnemials lead to a sensation of overall instability in 67% of patients and ankle instability in 25%.

Functional instability

Functional stabilization includes the muscle structures, an integral part of a much more complex system, proprioception, an element in postural control. Proprioception is a system comprising receptors, pathways, and nerve centers involved in perception, conscious or unconscious, of the relative position of the body parts in relation to each other [54—58].

Four types receptors exist in the ankle: the neuromuscular spindles, the Golgi tendon organs, the Ruffini joint mechanoreceptors, and the plantar cutaneous mechanoreceptors. Vision and the vestibular system should be considered indispensable postural information systems that must be evaluated during the examination. The reflexes induced by these receptors are more or less rapid depending on whether they use a rapid suprasegmental unconscious pathway or a conscious, and slower, cortical pathway. The myotatic reflex is the best known. At the same time, this reflex stimulates the antagonist muscles to encourage their release. During a forced inversion mechanism, the fibularis muscles and extensors of the toes are stretched, inducing reflexive tension of these muscles in the release of the posterior tibial muscles and the flexors of the toes. The Golgi tendon organs, located at the tendon—muscle junction, regulate muscle tension to protect the tendon from overstretching. The joint mechanoreceptors, which are sensitive to speed, direction, and range of motion, are only stimulated during extreme movements. These reflexes are therefore essential to protecting joints. However, after the study conducted by Thonnard [59], several authors [60,61] demonstrated that none of the neuromuscular responses to ankle varus was fast enough to prevent ligament injury, which occurs in 30 ms. They demonstrated the existence of muscle preactivation, which appears during dynamic movement 100 ms before landing (electromyographic analysis while running and hopping). The cutaneous mechanoreceptors involved in proprioception are well known and possess their own functions: some are more sensitive to stretching the skin (Merkel, Ruffini), others are more sensitive to vibrations (Pacini). It should be noted that the sole of the foot has sensory innervation in five areas, which makes it possible to discern pressure zones and consequently the position of the foot. Plantar sensitivity informs the central nervous system of shear forces and directions. Wang and Lin [62] noted that chronic instability increases if there is a reduction in plantar sensitivity, particularly with the eyes closed.

How can proprioception be clinically assessed? Upright monopodal stance should be tested with the eyes closed to provide a semeiologic value. Repeated hopping on one foot [63] seems to be the most reliable exam because it analyzes preactivation of the ankle's stabilizer muscles (fibularis, posterior tibia, and sural triceps muscles). Finally, Wang et al. noted a reduction in proprioception in obese subjects [64].

Functional muscular instability. The delay in muscle reactivity can be caused by a sometimes transitory neurological deficit (paresis after sitting with the legs crossed) or a mechanical muscle defect (muscle belly developed too dis-

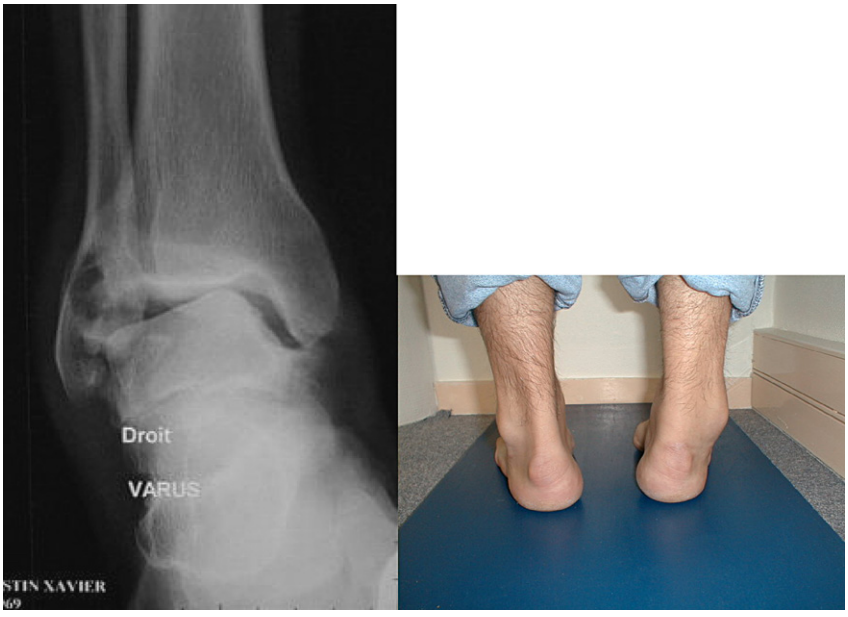


Figure 9 Varus of the hindfoot: failure of short fibularis muscle reconstruction because hindfoot not corrected.

tally, tenosynovitis or luxation of the fibularis muscles). In a gait analysis, Morrison and Kaminski [65] reported on the significant factors of instability: an increase in dorsal flexion of the first metatarsophalangeal joint, an increase in ground contact time, lateralization of pressure of the lateral edge of the midfoot and the forefoot, and an increase in the pronosupination index.

Functional postural instability. Varus of the hindfoot (Fig. 9) is a cause of ligament reconstruction failure [66]. Varus results in excessive pressure on the lateral edge of the foot and postural imbalance in monopodal weightbearing. It is responsible for excessive tension of the fibularis muscles, with most often a loss of the myotatic reflex or, on the contrary, a reflex excess with contracture of the fibularis muscles such as in sinus tarsi syndrome [67]. The associated equinus results in a contraction defect in the extensor digitorum muscles or, conversely, excess flexion with clawing of the lateral toes. Clawing of the fifth toe or a callus under the head of the fourth metatarsal is also a sign of ankle instability. Other morphostatic problems induce excessive pressure on the lateral edge of the foot such as unequal length of the lower limbs in which the shorter limb tends to position itself in varus-equinus, with genu varum, adductus foot, or forefoot pronatus, causing an unstable dynamic supination movement on weightbearing.

Conclusion

Through interrelated anatomical, mechanical, and functional factors, the pathomechanics of ankle instability is complex but also difficult to assess because few significant tests have been developed [68]. This can explain the recurrence of sprains and sometimes certain ankle ligament reconstruction failures. These failures should motivate us to conduct more extensive tests, both anatomical and functional. However, during treatment of chronic instability, certain fundamental rules must be kept in mind: not overly ''tighten'' ankle ligaments in reconstruction procedures so as to preserve proprioceptive reflexes, position tendon transfers so that the joint biomechanics of the talocrural and the subtalar are not modified, balance the muscular deficits, and finally realign to provide postural balance.

Conflict of interest statement

None.

References

[1] Willems TM, Witvrouw E, Delbaere K, Mahieu N, De Bourdeauhuij I, De Clercq D. Intrinsic risk factors for inversion ankle sprains in male subjects: a prospective study. Am J Sports Med 2005;33:415—22.

[2] Willems TM, Witvrouw E, Delbaere K, Philippaerts R, De Bourdeauhuij I, De Clercq D. Intrinsic risk factors for inversion ankle sprains in females: a prospective study. Scand J Med Sci Sports 2005;15:330—45.

[3] Bozkurt M, Doral MN. Anatomic factors and biomechanics in ankle instability. Foot Ankle Clin N Am 2006;11:451—63.

[4] Barbaix E, Van Roy P, Clarys JP. Variants of anatomical elements contributing to subtalar joint stability: intrinsic risk factors for post-traumatic lateral instability of the ankle. Ergonomics 2000;43:1718—25.

[5] Baumhauer JF, Alosa DM, Renstrom PAFH, Trevino S, Beynnon B. A prospective study of ankle injury risk factors. Am J Sports Med 1995;23:564—70.

[6] Hollis JM, Blasier RD, Flahiff CM. Simulated lateral ankle ligamentous injury: change in ankle stability. Am J Sports Med 1995;23:672—7.

[7] Maestro M. Rappel biomécanique des articulations talo-crurale et sous-talienne. Med Chir Pied 2004;20:6—10.

[8] Léardini A, Stagni R, O'Connor JJ. Mobility of the subtalar joint in the intact ankle complex. J Biomech 2001;34:805—9.

[9] Close JR. Some applications of the functional anatomy of the ankle joint. J Bone Joint Surg Am 1956;38:761—71.

[10] Inman VT. The joints of the ankle. Baltimore: Williams and Wilkins; 1976.

[11] Sarrafian SK. Anatomy of the foot and ankle. 2nd ed Philadelphia: JB Lippincott; 1993.

[12] Bonnel F. Anatomy of the forefoot. In: Cahiers d'enseignement de la Sofcot. Paris: Expansion scientifique française; 1997. p. 1—19.

[13] Barnett C, Napier JR. The axis of rotation at the ankle joint in man: its influence upon the form of talus and mobility of fibula. J Anat 1952;86:1—9.

[14] Hicks JH. The mechanics of the foot. I. The joints. J Anat 1953;87:345—57.

[15] Carret JP. Étude cinématique de l'articulation tibio-tarsienne. In: Cheville et médecine de rééducation. Paris: Masson; 1982. p. 7—9.

[16] Burks RT, Morgan J. Anatomy of the lateral ankle ligaments. Am J Sports Med 1994;1:72—7.

[17] Milner CE, Soames RW. Anatomical variations of the anterior talofibular ligament of the human ankle joint. J Anat 1997;191:457—8.

[18] Taser F, Shafiq Q, Ebrahein NA. Anatomy of lateral ankle ligaments and their relationship to bony landmarks. Surg Radiol Anat 2006;28:391—7.

[19] Wiersma PH, Griffioen FMM. Variations of three lateral ligaments of the ankle. A descriptive anatomical study. The Foot 1992;2:218—24.

[20] Pisani G. The coxa pedis. Eur J Foot Ankle Surg 1994;1:67—74.

[21] Mabit C, Boncoeur-Martel MP, Chaudruc JM, Valleix D, Descottes B, Caix M. Anatomic and MRI study of the subtalar ligamentous support. Surg Radiol Anat 1997;19:111—7.

[22] Sammarco GJ, Burstein AH, Frankel VH. Biomechanics of the ankle: a kinematic study. Orthop Clin North Am 1973;4:75—96.

[23] Fitzgerald E, Chao EY, Hoffman RR. Goniometric measurement of the ankle motion. A method of clinical evaluation. Trans Orthop Res Soc 1977, 23—43.

[24] Parlasca RJ, Morry AF, Takahashi K, Chao EY. Three dimensional kinetic analysis of the unloaded ankle and subtalar joints. In: Transaction of the 28th annual meeting of the Orthopedic Research Society. 1982.

[25] Mc Cullough CJ, Burge PD. Rotatory instability of the load bearing ankle, an experimental study. J Bone Joint Surg Brit 1980;62:460—4.

[26] Lundberg A, Svensson OK, Nemeth G, Selvik G. The axis of rotation of the ankle joint. J Bone Joint Surg Brit 1989;71:94—9.

[27] Huson A. Functional anatomy of the foot. In: Jahss disorders of the foot and ankle. 2nd ed. WB Saunders; 1991 [Chap. 15].

[28] Michelsen JD, Ahn UM, Helgemo SL. Motion of the ankle in a simulated supination-external rotation fracture model. J Bone Joint Surg Am 1996;78:1024—30.

[29] Van Langelaan EJ. A kinematical analysis of the tarsal joints: an X-ray photogrammetric study. Acta Orth Scand 1983;54(Suppl. 1):1—204.

[30] Ledoux WR, Sangeorzan BJ. Clinical biomechanics of the peritalar joint. Foot Ankle Clin 2004;4:663—83.

[31] Engsberg JR. A biomechanics analysis of talocalcaneal joint in vitro. J Biomech 1987;20:429—42.
[32] Léardini A, O'Connor JJ, Catani F, Giannini S. The role of the passive structures in the mobility and stability of the human ankle joint: a literature review. Foot Ankle Int 2000;7: 602—15.
[33] Hertel J. Functional anatomy, pathomechanics and pathophysiology of lateral ankle instability. J Athl Train 2002;37:364—75.
[34] Hubbard TJ, Hertel J. Mechanical contributions to chronic lateral ankle instability. Sports Med 2006;36:263—77.
[35] Kumai T, Takakura Y, Rufai A, Milz S, Benjamin M. The functional anatomy of the human anterior talofibular ligament in relation to ankle sprains. J Anat 2002;200:457—65.
[36] Van den Bekeron MPJ, Oostra RJ, Alvarez PG, Van Dijk CN. The anatomy in relation to injury of the lateral collateral ligaments of the ankle: a current concept review. Clin Anat 2008;21:619—26.
[37] Konradsen L, Voigt M. Inversion injury biomechanics in functional ankle instability: a cadaver study of simulated gait. Scand J Med Sci Sports 2002;12:329—36.
[38] Van den Hoogenband CR, Van Moppes FI, Stapert JW, Greep JM. Clinical diagnosis, arthrography, stress examination and surgical findings after inversion trauma of the ankle. Arch Orthop Trauma Surg 1984;103:115—9.
[39] Leland RH, Marymont JV, Trevino SG, Varner KE, Noble PC. Calcaneocuboid stability: a clinical and anatomic study. Foot Ankle Int 2001;22:880—4.
[40] Lohrer H, Nauck T, Arentz S, Vogl TJ. Dorsal calcaneocuboid ligament versus lateral ankle ligament repair: a case-control study. Br J Sports Med 2006;40:839—43.
[41] Tropp H. Functional ankle instability revisited. J Athl Train 2002;37:512—5.
[42] Beynnon BD, Murphy DF, Alosa DM. Predictive factors for lateral ankle sprains: a literature review. J Athl Train 2002;37: 376—80.
[43] Frigg A, Frigg R, Hintermann B, Barg A, Valderrabano V. The biomecanical influence of tibio-talar containment on stability of the ankle joint. Knee Surg Sports Traumatol Arthrosc 2007;15:1355—62.
[44] Frigg A, Magerkurth O, Valderrabano V, Lederman HP, Hintermann B. The effect of osseous ankle configuration on chronic ankle instability. Br J Sports Med 2007;41:420—4.
[45] Scranton PE, McDermott JE, Rogers JV. The relationship between chronic ankle instability and variations in mortise anatomy and impingement spurs. Foot Ankle Int 2000;21:657—64.
[46] Lebrun Ch, Krause J. Variations in mortise anatomy. Am J Sports Med 2005;33:852—5.
[47] McDermott JE, Scranton PE, Rogers JV. Variations in fibular position, talar length and anterior talofibular ligament length. Foot Ankle Int 2004;25:625—9.
[48] Hubbard TJ, Hertel J, Sherbondy P. Fibular position in individuals with self-reported chronic ankle instability. J Orthop Sports Ther 2006;36:3—9.
[49] Uys HD, Rijke AM. Clinical association of acute lateral ankle sprain with syndesmotic involvement. A stress radiography and MR Imaging study. Am J Sports Med 2002;30:816—22.
[50] Blaimont P, Libotte M, Klein P. Biomécanique de la tibiotarsienne. Implications cliniques. In: Cahiers d'Enseignement de la Sofcot. Paris: Masson; 1986. p. 21—36.
[51] Hintermann B. Biomechanics of the unstable ankle joint and clinical implications. Med Science Sport Med 1999;31:459—69.
[52] Mabit C, Boncoeur-Martel MP, Desnoyers V, Chaudruc JM, Bouillet Ph, Preux P. Subtalar ligaments: normal and pathological MRI findings. Radiology 1998;209:613.
[53] Barouk LS, Barouk P, Toullec E. Brièveté des muscles gastrocnémiens et pathologie de l'avant-pied : la libération proximale chirurgicale. Med Chir Pied 2006;21:143—52.
[54] Delmas A. Voies et centres nerveux. 10th ed. Paris: Masson; 1981.
[55] Richie Jr DH. Functional instability of the ankle and the role of neuromuscular control: a comprehensive review. J Foot Ankle Surg 2001;40:240—51.
[56] Willems T, Witvrouw E, Verstuyft J, Vaes P, De Clercq D. Proprioception and muscle strength in subjects with a history of ankle sprains and chronic instability. J Athl Train 2002;4:487—93.
[57] Liu YW, Jeng SC, Lee AJY. The influence of ankle sprains on proprioception. J Exerc Sci Fit 2005;3:33—8.
[58] McKeon PO, Hertel J. Systematic review of postural control and lateral ankle instability. Part II: is balance training clinically effective? J Athl Train 2008;3:305—15.
[59] Thonnard JL. Pathogénie de l'entorse du ligament latéral externe de cheville. Thèse de Docteur en réadaptation. Université de Louvain ; 1988.
[60] Vaes P, Duquet W, van Gheluwe B. Peroneal reaction times and eversion motor response in healthy and unstable ankles. J Athl Train 2002;4:475—80.
[61] Raugust JD. The effect of functional ankle instability on peroneal reflex latency. UAHSJ 2006;3:16—9.
[62] Wang TY, Lin SI. Sensitivity of plantar cutaneous sensation and postural stability. Clin Biomech 2008;23:493—9.
[63] Jerosch J, Bischof M. Proprioceptive capabilities of the ankle in stable and unstable joints. Sports Exerc Inj 1996;2:167—71.
[64] Wang L, Li JX, Xu DQ, Hong YL. Proprioception of the ankle and knee joints in obese boys and nonobese boys. Med Sci Monit 2008;14:129—35.
[65] Morrisson KE, Kaminski TW. Foot characteristics in association with inversion ankle injury. J Athl Train 2007;42:135—42.
[66] Vienne P, Schoniger R, Helmy N, Espinosa N. Hindfoot instability in cavovarus deformity: static and dynamic balancing. Foot Ankle Int 2007;28:96—102.
[67] Kjaersgaard-Andersen P, Wethelund JO, Helmig P, Soballe K. The stabilizing effect of the ligamentous structures in the sinus and canalis tarsi on movements in the hindfoot — An experimental study. Am J Sport Med 1988;16:512—7.
[68] Denegar CR, Miller SJ. Can chronic ankle instability be prevented? Rethinking management of lateral ankle sprains. J Athl Train 2002;37:430—5.