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The Role of the Passive Structures in the Mobility and Stability of the Human Ankle Joint: A Literature Review

Alberto Leardini[1], John J. O'Connor[2], Fabio Catani[1], and Sandro Giannini[1]

Bologna, Italy

ABSTRACT

The mobility and stability of the ankle joint have been extensively investigated, but many critical important issues still need to be elucidated. However, there seems to be a general agreement on several important observations. A more isometric pattern of rotation for the calcaneofibular and the tibiocalcaneal ligaments with respect to all the others has been reported. Many recent studies have found changing positions of the instantaneous axis of rotation, suggesting that the hinge joint concept is an oversimplification for the ankle joint. A few recent works have also claimed anterior shift of the contact area at the tibial mortise during dorsiflexion, which would imply combined rolling and sliding motion at this joint. Many findings from the literature support the view of a close interaction between the geometry of the ligaments and the shapes of the articular surfaces in guiding and stabilizing motion at the ankle joint.

Key Words:
ankle, motion, ligaments, axis of rotation, articular contact

1. INTRODUCTION

The ankle complex plays a fundamental role in human locomotion[47]. Functionally, the two main joints are the ankle and the subtalar complex between the talus and the calcaneus. Ankle injuries are among the most common, particularly in sport. They constitute between 10% and 15% of all injuries in sport with 85% of these involving sprains of the lateral ligament complex[129, 25]. Unsatisfactory results of total ankle replacement arthroplasty[10, 80, 91, 76,136] also highlight the need for more adequate knowledge of the anatomical and biomechanical characteristics of this joint.

Joint *mobility* is the primary goal of joint replacement and ligament reconstruction. A disappointing range of movement in the replaced ankle joint results from the continued presence of contracted soft tissue around the joint[56]. *Stability*, joint resistance to relative movement of the bones when load is applied, is the other primary requirement of joint replacement. Its restoration is also the main justification for ligament reconstruction. Passive stability, as assessed in a range of clinical tests, is a measure of the limitation imposed by the anatomical structure and therefore involves mechanical interactions between ligaments and articular surfaces and reflects both the integrity of those structures and their mechanical properties. Active stability involves mechanical interactions *between muscles, ligaments and articular surfaces* in response to external forces of gravity. Rational design of both ligament reconstructions and joint replacements therefore demands understanding of the interactions between the ligaments and articular surfaces of the joint. Restoration of normal joint function and range of motion requires re-establishing the natural relationships between the geometry of the articular surfaces and the geometry of the ligaments. Concurrent techniques of ligament reconstruction and the wide variety of design of ankle prosthesis available today suggest that these geometric relationships are not yet fully understood.

A very large range of different terms and conventions have been used to describe ankle and foot rotations. The following terminology is an attempt to avoid misinterpretation. In the present paper, the ankle joint is synonymous with the talocrural joint, that is the multiple articulations between tibia, fibula and talus bones. The rotations of foot joints in the sagittal plane about the medio-lateral axis are designated as *dorsi/plantarflexion (DP). Pronation and supination (PS)* are the rotations which occur in the frontal plane about the antero-posterior axis. *Internal and external rotation (IE)* occurs in the transverse plane about a vertical axis. The typical tilting motions, achieved by the combined and coupled rotation of several foot joints, is termed as *inversion/eversion*.[4]

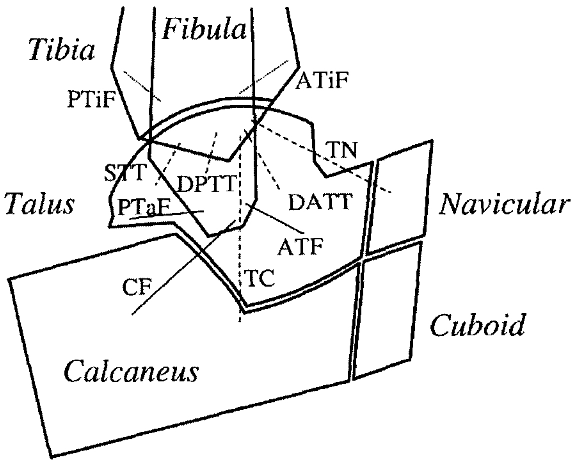
2. LIGAMENTS

The Ligaments section describes basic anatomy of the ligamentous structures surrounding the ankle, together

Corresponding author:
Alberto Leardini, M.Eng.; Movement Analysis Laboratory, Istituti Ortopedici Rizzoli, Bologna, Via di Barbiano 1/10 40136 Bologna, Italy
Tel: +39 051 6366522
Fax: +39 051 6366561
E-mail: leardini@ior.it

[1]Movement Analysis Laboratory, Istituti Ortopedici Rizzoli, Bologna, Italy
[2]Oxford Orthopaedic Engineering Centre, University of Oxford, U.K.

with reported results on their roles in joint stability and their elongation during joint rotation.



Schematic representation of the ligaments of the human ankle complex. Lateral (solid), medial (dashed) and tibiofibular (dotted) ligaments are indicated.

2.1 Lateral and posterior side

The lateral aspect of the ankle capsule is augmented by the anterior and posterior talofibular ligaments and by the calcaneofibular ligament. Of these three structures, the anterior talofibular and the calcaneofibular ligaments are considered the most important stabilizing structures [102].

- Calcaneofibular ligament (*CF*). The CF is an extra-capsular styloid shaped ligament. Its average length and width was recently reported to be respectively 24.3 and 6.7 mm by Buzzi et al.[21], and 35.8 and 5.3 mm by Burks et al.[20]. From the anterior edge of the distal fibula, the ligament extends obliquely downward, backward and medially to the mid-lateral surface of the calcaneus. The origin is located just in front of (anterior to) the apex of the lateral malleolus, with its anterior fibers converging to the same point of the ATF lower fibers. The direction of the projections of the ligament and the subtalar joint axis in the sagittal plane are almost parallel, and retain their parallelism as the ankle passes from plantarflexion to dorsiflexion[163]. Early clinical studies on its role in ankle joint stability thought that it was slack until a supination force was applied[16]. In an extensive review of the literature on ankle joint stability in 1985, Rasmussen[120] reported that the CF is expected to inhibit supination, though it is uncertain whether it has this function as long as the other ligaments are intact. Also its role in DP was uncertain. He concluded that the CF hardly plays any independent role in the stability of the ankle. It limits supination together with the ATF in plantarflexion and in neutral position, and together with the PTaF in dorsiflexion. Stormont et al.[164] stated that, in the unloaded state, the CF is the primary restraint to external rotation and to supination of the ankle complex. In agreement with Rasmussen, Stephens and Sammarco[162] have recently pointed out that the CF contributes to ankle stability in all positions, but together with the PTaF. Because of its anatomical orientation, the CF also has a major role in the stabilization of the subtalar joint[86, 59]. Kjaersgaard-Andersen et al.[77] reported that the transection of this ligament resulted in increased supination at the subtalar joint of up to 77%, proving its additional role in providing lateral stability to this joint. However, this finding is in contrast to that of Cass et al.[24], who found no such influence on the subtalar joint. This discrepancy may be related to the anatomical variability of the orientation of the ligament as analyzed by Ruth[137], and to the variable anatomic relationship between the CF and the lateral talocalcaneal ligament (LTC) as investigated by Tronilloud et al.[169]. The latter study reported that the CF blends with the LTC and diverted from the latter only at the talar or at the calcaneal insertion in 9 (35%) of the 26 ankles studied. They also reported a group of 7 (25%) of the specimens with totally distinct fibers, and even LTC absence in the remaining 10 (40%) of the specimens. Transection of the CF did not affect the subtalar motion in the second group, whereas it resulted in a talonavicular subluxation in the first and third group. Conflicting results were reported so far in the literature also regarding the effect of isolated rupture of the CF on the mechanical characteristics of the ankle joint. Rasmussen[124] found no significant changes in the range of motion of the ankle, in contrast with Siegler et al.[155] who reported increase in DP, PS and IE respectively of 8, 15, 5% of the motion in the intact joint.

The elongation and strain patterns of the CF in ankle joint motion is controversial. Renstrom et al.[129] measured the strain in the lateral ligaments of the ankle using Hall-Effect strain transducers attached in the middle portion of each ligament. They found that the CF is essentially isometric (increasing strain from the neutral position less than 1%) during pure DP, i.e. without PS and rotation of the foot. As expected, Renstrom et al. and also Colville et al.[30] reported a significant increase of ligament strain in supination and external rotation, but with a decreasing effect as the ankle joint plantarflexes. Nigg et al.[107] measured the length changes of the anterior fibers of the CF using syringe needles, dividers and ruler. They described the ligament length as sensitive to excessive PS and DP. They also tested the ligament force-extension pattern in isolated bone-ligament-bone preparations, simulating anatomical position and orientation of the bones. From 15º of dorsiflexion to 30º of plantarflexion, its length increased by 26% of the maximum length change. Colville et al. presented strain measurement data of all the lateral ankle ligaments when the foot was moved from complete dorsiflexion to plantarflexion. In agreement with Renstrom et al., they reported a progressively decreased strain of the CF (6% of its strain in the most lax position) when the ankle moved from 20º dorsiflexion to 10º plantarflexion, and a slight increase (1%) in the final plantarflexion. The large difference between the values reported by Renstrom et al. and Colville et al. may be related to the two different assumptions for the zero value of ligament strain. The former chose the strain in the neutral position of the ankle while the latter adopted the strain measured in its most lax position. Cawley and France[25] studied the strain behavior of lateral ligaments of the ankle with and without external load using Hall-Effect transducers. Ligaments were instrumented rather than selectively sectioned so that coupling behavior could also be evaluated. They reported values of 0.35% and 1.2% in CF strain in 30º plantarflexion and 20º dorsiflexion respectively. Ozeki et al.[109, 110] used strain gauge transducers to measure strain changes in the fibers of the CF and ATF in twelve amputated lower-limb specimens during manually driven DP. They reported strain values of 3.2, 5.6 and 9.3 % for the anterior, central and posterior fibers of the CF respectively. Two recent papers[17, 21] gave a more detailed description of the elongation pattern of the different fibers of the ligament using respectively spring loaded isometers and position measurements from X-rays. In both experiments, the ankle was manually moved throughout its complete physiological range of motion. Bruns and Rehder[17] found that, during complete ankle motion from 30º of dorsiflexion to 40º of plantarflexion, the elongation of its anterior, middle and posterior fibers all are less than 1/10 of the corresponding maximal length. Buzzi et al.[21] reported an increase in the distance between insertions of its anterior, central, and posterior fibers in dorsiflexion, being 3.4%, 8.5%, and 16.9% of the corresponding length in neutral ankle position respectively, in general agreement with the results of Ozeki et al.. It is important to note that, in this latter study, a compressive force was applied through the foot to keep the talus well seated within the mortise. The most recent study[42] measured the forces in the CF during simulated weight-bearing foot positions in eight specimens. In all the DP positions and in both the neutral and 150 pronation foot positions, the tension force in the ligament was found to be less than 20 N. These results should however be taken with caution because of the artifacts involved in buckle transducer measurements. Recently Luo et al.[99] have examined the elongation of the main ankle ligaments induced by different foot maneuvers. They reported an average elongation among the eleven cadaver feet analyzed of only 19 mm from neutral to maximal dorsiflexion position. No elongation was observed from neutral to maximal plantarflexion position.

- **Anterior talofibular ligament (*ATF*)**. The ATF is approximately 7 mm wide and 25 mm long[20] and situated in the anterolateral joint capsule. From the anterior edge of the lateral malleolus, just lateral to its articular cartilage and between the CF and ATF insertion areas, it extends slightly superiorly, anteriorly and medially to the lateral aspect of the talar neck between the lateral articular facet and the mouth of the sinus tarsi[20]. This recent detailed description is in contrast to previous reports[71, 120, 21], which stated that the ligament extends slightly superiorly. In plantarflexion, it is parallel to the long axis of the foot, whereas in dorsiflexion, it is aligned at approximately right angles to the tibial and fibular shafts[163].

The ATF is the most important stabilizer of the ankle[16] and the most frequently involved ligament in an inversion injury. In contrast to all earlier works, two different cadaver sectioning studies[70, 150] found the ATF to be the primary restraint to supination and anterior talar translation at all positions of flexion. Rasmussen[120] stated that the ligament limits plantarflexion as well as internal rotation of the talus, and it appears to exert an inhibitory function in dorsiflexion which tightens its most plantar fibers. Stormont et al.[164] stated that, in the unloaded joint state, the primary restraint to internal rotation is the ATF. Recent studies have reported contrasting results: Stephens et al.[162] has pointed out its contribution in ankle stability only in plantarflexion, whereas Hollis et al.[62] found increase in ankle and subtalar motion after its sectioning, mainly in dorsiflexion.

Most papers mentioned above as studies on CF elongation reported also corresponding results for the ATF. Renstrom et al.[129] reported that the ligament undergoes an increase in strain of 3.3% from 10º of dorsiflexion to 40º of plantarflexion. Nigg et al.[107] stated that the elongation of its most anterior fibers is sensitive to DP motion: the length increased by 46% of its maximum length. Colville et al[30] reported, again in agreement with Renstrom et al., a progressive increase in the strain during the complete motion from maximal dorsiflexion to maximal plantarflexion. Cawley and France[25] reported values of 3.3% and 0% in ATF strain[34] in 30º plantarflexion and 20º dorsiflexion positions respectively. Ozeki et al.[110] reported strain values of 15.1, 8.5, 1.9 for the superior, central and inferior fibers of the ATF respectively. Also Bruns and Rehder[17] reported on the anisometric characteristics of the ATF fibers. During plantarflexion the most plantar fibers showed a shortening of almost four tenths of the relevant length in maximal dorsiflexion, whereas the fibers located more dorsally showed a shortening of only one tenth of the relevant maximal length during dorsiflexion. However, Buzzi et al.[21] found different results. They found an increase in the distance between the insertions of its superior fibers in plantarflexion (8.9% on average), while the distances between the insertions of the central and inferior fibers showed minor changes (less than 3.5%), in general agreement with Ozeki et al. It has also been suggested that supination and internal rotation moments applied to the ankle increase the strain in this ligament[129, 30]. In a recent study, Engebretsen et al.[42] measured the forces in the ATF in different foot positions with or without compressive load in eight specimens. The tension force reached about 40 N in 20º plantarflexion both in 15º foot supination and neutral PS positions. In all DP positions and in 15º pronation the force was found to be less than 30 N. Axial loading increased the measured forces. The results showed that ATF acted as a primary restraint in the inverted position. Luo et al.[99] reported an average elongation of 5 mm from neutral to maximal plantarflexion position.

- **Posterior talofibular ligament (*PTaF*).** The PTaF is a normal variant of the posterior ligaments of the ankle and is present in a significant (56%) number of persons[133]. It is a strong, intracapsular ligament originating in the fossa of the lateral malleolus and spreads in the shape of a fan. Its anterior, short fibers insert laterally on the posterior edge of the talus and its posterior, long fibers medially on the lateral tubercle of the posterior process of the talus. Rasmussen[120] stated that this ligament seems to have little influence upon ankle stability. Only in dorsiflexion does it exert a restricting function upon external rotation. As mentioned above, it was found to contribute to ankle stability together with the CF, in all the DP positions. Colville et al.[30] reported its increase in strain both from neutral position to maximal dorsiflexion (about 7%) and from neutral to maximal plantarflexion (less than 5%). Buzzi et al.[21] reported an increase in the distance between the insertions of its long fibers in dorsiflexion (+9.9%), but, in contrast to Colville et al., they reported a slight strain decrease in plantarflexion (-2.3%). Luo et al.[99] reported a moderate elongation during flexion.

Several authors[67,121, 70] agree that talar tilt is limited in plantarflexion and in neutral position by the ATF, and in dorsiflexion by the CF plus the PTaF. Tightening of the ATF in plantarflexion and of the CF in dorsiflexion, has been observed by many authors[101, 120, 70,129, 25, 31, 21]. Only Bruns and Rehder[17] found slackening of the ATF in plantarflexion. Buzzi et al.[21] concluded their investigations by suggesting that the ATF and CF work together in a synergistic fashion to provide lateral stability to the ankle throughout the full range of motion, in such a way that when one is relaxed the other is strained and vice versa. Similar descriptions were given in other reports[152,129, 30, 19, 25].

Looking at the role of these ligaments in DP motion, Lapidus[83] postulated that CF, ATF, and PTaF are arranged like spokes of the wheel converging on the tip of the lateral malleolus at the same position of the axis of rotation. They were therefore expected to be equally tense within the entire range of ankle DP. However, results reported by Renstrom et al.[129] and Colville et al.[30] are also in general agreement with many others[107, 25, 110, 17, 42, 99] who described the more isometric/ isotonic pattern of rotation of the CF with respect to the ATF, i.e. strain in the ATF in maximal plantarflexion is bigger than CF strain in maximal dorsiflexion. Moreover, axial load in neutral position significantly increases ATF strain but does not increase CF strain[25]. Buzzi et al.[21] stated that lateral ligaments of the ankle are not isometric, but they found fibers both in CF and ATF that showed very small length changes. However, it is important to emphasize that all the ligament elongation and strain measurements were carried out during ankle motion induced by the application of externally controlled moments to the foot about the three anatomical axes: no attempts were done to evaluate ligament fibers elongating during unresisted ankle motion. Only in this condition does the joint move according to the geometry of the articular surfaces and to the arrangement of the ligaments and therefore only in this state it would be possible to detect the ligament fibers that dictated the joint motion.

Several other studies have shown that the CF plays a more important role than the ATF in guiding sagittal plane rotations. Chen et al.[26] reported significant differences in the flexibility characteristics of the ankle joint, before and after the ATF sectioning, only in the transverse and frontal plane rotations. Rasmussen and Tovborg-Jensen[124] surprisingly found that sectioning of the ankle lateral ligaments increases only the range of dorsiflexion, while plantarflexion remains unchanged. Moreover, a further investigation by Chen et al.[155] showed that only the sectioning of the CF causes a large decrease in the kinematic coupling of the ankle joint, proving its fundamental role in guiding joint motion.

Interesting results come also from investigations on tensile mechanical properties of lateral ligaments and from the well known 'tibiotalar delay'. The ultimate load was found by Siegler et al.[153] to increase in anteroposterior sequence, but in the ATF, PTaF, CF sequence by Attarian et al.[7] the CF was found from both to have the highest linear modulus of elasticity among the lateral side ligaments, indicating a ligamentous stiffness during physiologic functions. The so-called 'tibiotalar delay'[171, 65, 66, 64] could also account for the slackening of the ATF and STT in ankle positions between the extremes of the range of motion. The talus does not follow immediately a manually externally imposed rotation of the tibia, but only after an angular 'delay'. With the ankle in its neutral position, the fibers of the ATF and STT ligaments have to tighten before motion of the talus is observed. All these experimental observations demonstrate the main role of the CF in guiding ankle rotations.

2.2 Medial side

The deltoid ligament is a large and strong ligament, spreading fan-shaped over the medial part of the ankle joint. It originates on the medial side of the medial malleolus and inserts on the navicular, talus and calcaneus. Because the origins and insertions of its different parts are contiguous and not sharply demarcated from each other, wide variations in its anatomical descriptions have been noted in the literature. In the present paper we will consider the view of Pankovich and Shivaram[112], who provided the most detailed and comprehensive description of the anatomy of the deltoid ligament. They discussed the five different descriptions previously adopted, and proposed the view of the in deltoid ligament as formed by two different portions: the deep and the superficial, having respectively two and three different ligament bands. The superficial portion originates on small bony prominences that protrude from the distal ridge of the medial malleolus, called 'collicula'. This description has been later followed by many other researchers[120, 139,163].

- **Tibionavicular ligament (*TN*)**. The band of the TN originates from the anterior colliculus of the medial malleolus, extends in a fan-shape fashion and forms a triangular ligament which is inserted into the dorsomedial surface of the navicular and along the dorsomedial surface of the plantar calcaneonavicular ligament. It is the largest and widest portion of the superficial part of the deltoid ligament. It is rarely included in the list of ligaments relevant for ankle joint stability. Pankovich and Shivaram observed it becomes taut when the foot is plantarflexed. Quiles et al.[118] measured the elongation of all the different fibers of the deltoid ligament and stated that its most anterior fibers tighten as the ankle plantarflexes, and the reverse occurs in dorsiflexion. They reported 10 mm change in length for both the two motions. Recently Luo et al.[98, 99] have demonstrated that the TN performs the most significant response to ankle plantarflexion (6 mm of elongation from ligament length in foot neutral position). For dorsiflexion, PS and anterior drawer maneuvers the elongation was found to be less than 2.5 mm.

- **Tibiocalcaneal ligament (*TC*)**. The TC is the middle and the strongest of the three bands. It originates from the mid portion of the medial surface of the anterior colliculus and inserts along the medial border of the sustentaculum tali of the calcaneus[112]. It was found to restrict pronation and it can even rupture in isolation with pronation trauma[120]. Pankovich and Shivaram observed that most of the fibers become taut when the foot is plantarflexed while the posterior fibers are taut in dorsiflexion. Quiles et al.[118] stated that the ligament slackens as the ankle begins to plantarflex (2 mm decrease in length), and the reverse occurs in dorsiflexion (less than 1 mm increase in length). Nigg et al.[107] measured the change in length of the posterior fibers of the TC. In contrast with Quiles et al. results, they found 22% decrease in length in dorsiflexion and 13% increase in plantarflexion. According to Quiles et al., Bruns and Rehder[17] reported an almost isometric pattern of its anterior fibers and, a maximal shortening of its most posterior fibers in maximal plantarflexion (less than two tenths of the relevant maximal length). Although Luo et al.[98, 99] did not distinguish between different fibers, ligament elongation less than 3 mm was found for all the maneuvers, demonstrating the most overall isometric pattern of motion among the three parts of the deltoid ligament.

- **Superficial tibiotalar ligament (*STT*)**. This band originates from the posterior part of the medial surface of the anterior colliculus and the adjacent small part of the posterior colliculus. It takes a postero-distal course and inserts into the anterior portion of the medial tubercle of the talus. The ligament becomes taut when the foot is dorsiflexed while it slackens as the ankle plantarflexes[112, 118]. Bruns and Rehder[17] reported that all its fibers show an isometric pattern but found slackening as the ankle dorsiflexes (less than 3/10 of the relevant maximal length).

- **Deep anterior tibiotalar ligament (*DATT*)**. The DATT makes up the anterior portion of the deep layer of the deltoid ligament. It is a small and short band which is covered by the TC. It originates anteromedially and distally in the tibia epiphysis and proceeds distally and slightly forward to insert on the medial surface of the talus near its neck. In combination with the ATF, it appears to restrict both translatory forward gliding of the talus and plantarflexion of the ankle[120]. Pankovich and Shivaram[112] observed that this portion becomes taut when the foot is plantarflexed. Similarly, Luo et al.[98, 99] report a length change of 9.7 mm during plantarflexion, the largest length change of all the medial ligaments.

- **Deep posterior tibiotalar ligament (*DPTT*)**. The DPTT constitutes the posterior, deep portion of the deltoid ligament. It is a strong and thick ligament which extends posteriorly, laterally and distally from the posteromedial aspect of the medial malleolus to the posteromedial part of the talus. Both the DATT and the DPTT were found to be virtually intraarticular structures. The ligament is thought to prevent ankle internal rotation[120]. It also restricts dorsiflexion and may rupture in isolation in a dorsiflexion trauma. Pankovich and Shivaram[112] observed that it becomes taut when the foot is dorsiflexed.

Many authors[29, 52, 164] described the deltoid ligament to be a strong restraint to talar pronation. Rasmussen et al.[124, 122] investigated the function of the various parts of the deltoid ligament and stated that the TC specifically limits talar pronation while the deep layers of the deltoid ligament rupture in external rotation without the superficial portion being involved. Harper[57] claimed that the deltoid ligament is the primary restraint against pronation of the talus, but with superficial and deep components being equally effective in this regard. Nigg et al.[107] stated that the deltoid ligament appears to be sensitive to plantarflexion, external rotation, and pronation.

Lapidus[83] deduced that the posterior fibers of the deltoid ligament are tight in dorsiflexion and the anterior fibers in plantarflexion since he assumed the axis of DP to run mediolaterally at the level of the lateral malleolus, and therefore in between the posterior and anterior fibers of the deltoid. Two similar studies[118, 17] demonstrated a more isometric pattern of elongation of the TC compared with both the TN and STT. Also the results reported by Luo et al.[98, 99] for ankle DP, PS and anterior drawer maneuvers support this conclusion. Earli et al.[39] found that the TC sectioning produces the greatest changes in both contact area (decreased up to 43%) and peak pressure (increased up to 30%). Siegler et al.[153] reported the increasing order of ultimate load to be TC, TN, and STT. These observations emphasize the role of the TC in guiding ankle rotations on the medial side, as it does the CF on the lateral side.

2.3 Tibiofibular ligaments

The set of ligaments and membranes that keep the tibia and the fibula together is also called 'Syndesmosis'.

- **Interosseous membrane (*ITiF*)**. Its fibers originate in the greater part of the fibular notch of the tibia (the indentation of the lateral end of the tibia) and insert at the same level on the anterior two-thirds of the medial fibular surface. Lapidus[83] supposed that the observed obliquity of tibiofibular syndesmosis fibers may produce a slight proximal displacement of the fibula when they become taut.

- **Anterior tibiofibular ligament (*ATiF*)**. The ATiF is a strong ligament, about 20 mm wide and 20-30 mm long, originating on the anterior tubercle of the distal tibia and anterolateral part of the tibial epiphysis. Its fibers proceed in an oblique distal and lateral direction and insert anteromedially on the upper portion of the lateral malleolus. It is wider proximally than distally. The tibial insertion is placed along the anterior margin of the fibular notch, whereas the fibular insertion is placed along the anterior margin of the lateral malleolus, just above the fibular insertion of the ATF.

- **Posterior tibiofibular ligament (*PTiF*)**. The PTiF is a strong ligament measuring about 5 x 20 x 30mm which runs from the distal and lateral part of the tibial epiphysis in an oblique course distally and laterally to insert on the posterior surface of the lateral malleolus. The deep transverse tibiofibular ligament is here considered to be part of the PTiF, although Sarrafian[143] distinguishes between the 'deep transverse' and the 'superficial posterior' courses.

The ligamentous structure which includes the above three ligaments is also called 'distal tibiofibular syndesmosis'. Rasmussen[120] suggested that this structure plays only a little role in ankle stability, providing there is an otherwise intact ligamentous apparatus. They rarely rupture without the presence of injuries to other structures. Colville et al.[30] measured the patterns of strain during ankle motion and found a progressive small decrease in strain for the ATiF and the PTiF during ankle motion from maximal dorsiflexion to the neutral position (about 3%). A very little strain was also observed during plantarflexion[78]. External rotation of the talus rotated the fibula externally and strained the ATF, internal rotation of the ankle rotated the fibula internally and strained the PTiF.

2.4 Observations from the Authors and Conclusion

There is therefore suggestion in the literature that fascicles within the CF and TC remain isometric during ankle flexion. It has recently been shown by the present authors[90, 89] that these fascicles guide the motion of the articular surfaces on each other and determine the position of the axis of rotation relative to the bones. The patterns of slackening and tightening of the other ligament fibers described above depend on whether they pass anterior or posterior to that axis. It has also been shown[88] that the most anterior fibers of the CF and the TC are the most isometric fascicles and that they guide the motion of the articular surfaces, while other fibers have been observed to slacken as soon as the ankle starts to plantarflex.

3 ARTICULAR SURFACES AND CONTACT AREA

The main articulating surface of the ankle is the upper, formed by the distal articular surface of the tibia above (also referred to as the mortise) and the superior articular surface of the talus below (also referred to as the trochlea tali). The lateral and the medial joint surfaces are between the talus and the inner aspect of the lateral and medial malleoli respectively.

3.1 Curvature of the trochlea and the mortise

Barnett and Napier[8] examined the profiles of the trochlea tali in 152 specimens. On the lateral side, they found that only the posterior 70-80% of the profile fits a single circular arc, while the anterior 20-30% fits a shorter radius. The centers of the two arcs lie approximately 1 cm apart. On the lateral side, similarly with most of the literature, they found that the entire profile fits a single circular arc, with radius laying between the length of the two medial radii. They deduced that from neutral to maximal dorsiflexion, the arc of anterior third of the medial profile has a radius shorter than that of the lateral profile, so that the axis of rotation which passes through the two centers is inclined downwards and laterally. From neutral to maximal plantarflexion, the arc of the posterior two-thirds of the medial profile has a radius longer than that of the lateral profile, and the axis is inclined downwards and medially.

Inman[67] examined 104 cadaver specimens and reported that in tali with a single arc on the medial side, the difference of the radius curvature between the medial and the lateral is very small (2.1mm), but in no specimen was the medial greater than the lateral radius. Comparing the radii on the talus and on the mortise, Inman concluded that the talus fits snugly in the mortise on the lateral side but rather loosely on the medial side. Starting from these results and from the observed convergency of the saw cuts on the trochlea when the talus is rotated about the axis of rotation located empirically by means of a jig, he proposed the trochlea tali should be considered as the frustum of a cone whose apex is directed medially. He measured its apical angle and reported an average value of 24º (range 0-38º) for the talus and 22º for the mortise.

3.2 Trochlea width difference

Although the width difference between the anterior and posterior margins of the joint surface of the talar trochlea has long been recognized[15, 149], very few authors have provided measurements and the few values reported reveal large discrepancies. Barnett and Napier[8] measured the degree of 'wedging' in 152 talus specimens and found it ranging from 0 to 14%. Inman[67] confirmed the Barnett and Napier results, measuring an average difference of the width of the trochlea of 2.4 mm, with a range of 0-6 mm, using a plane perpendicular to the surface of the tibial facet. But he also pointed out that the difference tends to vanish (2 mm) when the measurements are taken along the conical surface of the trochlea. The results on the possible different width of trochlea tali have obvious implications for the parallelism of the medial and lateral facets of talus.

3.3 Medial and lateral facets

The wedging of the trochlea of the talus in the transverse plane raises the point of the geometrical configuration of the malleolar facets, whether there is articular congruity at the medial and lateral side. Inman[67] found that the angle between the 'empirical axis' of the ankle (see Section 'Axes of rotation') and the planes of the lateral and medial facet of the talus are 89º and 96º respectively, implying a convergence of 7º. He described a similar angle of posterior convergence of the malleolar facets, concluding that the malleolar and talar facets remain in contact throughout the entire range of ankle motion. This fit was also described by other authors[94, 103, 92]. A later extensive investigation from Reimann et al.[126, 127, 128] has questioned this concept. They described two completely different courses of motion, due to the non-congruent articular surfaces: in dorsiflexion, it is the tibia that leads the talus whereas the fibula is pushed laterally, while in plantarflexion the talus is led by the fibula and withdraws from the medial malleolus, remaining in close contact with the tibial roof. They later developed the model and described the medial facet of the talus as a flat cone and the lateral facet as a helicoidal face wider anteriorly, so as to push the lateral malleolus outward during dorsiflexion.

3.4 Mobility of the lateral malleolus

The apparent widening of the mortise in dorsiflexion due to the difference in width of the anterior and posterior parts of the trochlea has been pointed out by many authors[6, 52, 67, 72, 1]. Measurements of the lateral displacement of the fibula have been obtained using very different techniques, and the values reported[29, 52, 72, 95] are all in the range of 1-2 mm when the talus moves from maximal plantarflexion to maximal dorsiflexion. External rotation of the lateral malleolus was also observed by Barnett and Napier[8] (3º), Jend et al.[69] (4º) during ankle dorsiflexion, and by Close[29] (5-7º) when an external rotation force is applied to the talus. Antero-posterior translation of the fibula has also been noted[3]. Since the articular surface of the distal tibia covers only from one-half to two-thirds of the corresponding talar articular surface in the sagittal plane[29, 143], and since the difference between anterior and posterior widths of the trochlea is small, only a very small motion of the lateral malleolus is theoretically required during ankle flexion.

3.5 Contact areas

Because both the superior dome of the talus and the ankle articular surfaces of the tibia and fibula are complex anatomical structures, it is easy to conceive that hardly the ankle joint shows congruency throughout its range of motion. Quantitative measures on ankle contact areas have been obtained using dye injection into the joint capsule[51, 92], powered carbon black[119, 28, 32] and other cartilage staining techniques[54, 53], but mostly using pressure-sensitive films[74,172,165,167,18,100, 9, 23, 27, 37, 58,177, 44,116,115,11, 173]. They reported the size of the area of contact to be in the range between 1.5 and 9.4 cm^2 with ankle in neutral position and with axial load in the range between 445 and 2300 N. Only Greenwald et al.[54] reported larger tibiotalar contact area (11 to 13 cm^2) and ankle joint congruence for those loads. Other more recent studies[23, 100, 177] found that the contact area increases as the joint goes from plantarflexion to dorsiflexion. This differs from the results of other studies[9, 111], which reported a decrease in contact area for dorsiflexion and areas very similar to the ones in neutral position for plantarflexion. It also differs from those[37, 92] who reported significant decrease in contact area from neutral position for both plantarflexion and dorsiflexion. The large variation of the results reported seems related to the different range of loads applied but mainly to the different method utilized and to the inaccuracies involved in experiments using pressure sensitive films.

Although most of the papers have also shown, predictably, that the area of contact on the dome of the talus moves anteriorly during dorsiflexion, they all failed to provide any information on contact pattern on the tibial articular surface. Recent studies[75, 88, 79] were able to show contact area on both the articular surfaces using accurate bone position data and digitization of the relevant articular surfaces. The estimate of ankle contact area was based on the concept of proximity of articulating surfaces[144]. From the results of Kitaoka et al.[75, 79] studies, an anterior translation of the contact area on the mortise in dorsiflexion can be appreciated. This is in general agreement with a preliminary work from the authors[88] who found that contact area shifted from the posterior aspect of the mortise in plantarflexion to the anterior aspect in dorsiflexion. This observation is fundamental to demonstrate the rolling motion of the talus on the tibia. This important finding has also been recently elucidated by a mathematical model[89].

4 MOTION

4.1 Range of motion

The range of DP has been analyzed by several authors. The extent reported has differed appreciably due probably (a) to the different techniques used to measure the range of motion (simple radiographs[140, 174], roentgen stereophotogrammetry[95, 96], goniometers[12, 49, 93, 132, 148], stereoscopic techniques[4, 154], optical stereophotogrammetry[87, 145, 146]); (b) to the different testing conditions of the measurements[7] (*in-vivo* with and without weightbearing and in passive motion or during physical activities, *in-vitro* with and without load and in induced movements); (c) to the variations in the definitions of joint rotations; and finally (d) to the considerable variation in individual ankles reported by all the authors. The values found range from 23º to 56º of plantarflexion and from 13º to 33º of dorsiflexion. Because of the impossibility of tracking talus positions using non-invasive techniques, almost all the *in-vivo* investigations present measurements of the total sagittal plane rotations, that is those occurring between foot and shank, therefore including the subtalar and midtarsal joints.

Rotation about the vertical axis has often only been mentioned as a side effect of the inclination of the ankle joint axis[67,104]. Some other studies that refer to the ankle movement on planes other than sagittal, have generally dealt with instability of the joint rather than physiological motion[61, 63, 84, 85, 164]. However, many others[29, 70, 103, 124, 171] refer to it as an independent movement allowing one more degree of freedom, even though the results reported differ considerably.

4.2 Axes of rotation

There is a traditional controversy concerning the number of independent axes of rotation and their orientation. In the large majority of the early reports, the ankle joint was assumed to be an ideal hinge joint, possessing a single rotational degree of freedom. Pioneer studies on ankle motion[45, 50, 83, 149] postulated that the axis runs horizontally and orthogonal to the sagittal plane. Isman and Inman[67, 68] agreed with the previous hypothesis of a single fixed axis of rotation but introduced the idea of an oblique direction of the axis, running approximately through the tips of the two malleoli, therefore inclined downward and posteriorly in the sagittal plane and postero-medially in the transverse plane. This orientation would produce coupled movements: the ankle everts by dorsiflexing, pronating and externally rotating, while inverts by plantarflexing, supinating and internally rotating. It is important to emphasize that the authors estimated the location of the so-called 'empirical' axis in the hypothesis of a single unique position. They considered the articular surfaces to be the only guides of the motion and they did not take into account the possible contribution of the ligaments. They also reported a considerable individual variation. The approximation of the ankle as a simple hinge joint has been accepted in the description of rearfoot motion[36, 40, 41, 82, 104, 105, 108, 134, 175, 147, 158 ,178], has been adopted in many mathematical models of the ankle and foot[38, 48, 117, 145, 146, 161], and has been assumed also in the estimation of the orientation of the axis from the trajectories of external markers[5,170]. Finally, several designs of total ankle replacement[22, 73, 113, 159, 160,] have also been based on a cylindrical geometry with the relevant axis running exactly medio-laterally.

Moving from this original hypothesis, Barnett and Napier[8] and Hicks[60] found evidence that the ankle joint axis changes orientation close to neutral position between plantarflexion and dorsiflexion motion. They concluded that the axis of rotation may be assumed to run between the tips of the malleoli only in dorsiflexion, while it is inclined downwards medially in plantarflexion. Barnett and

Napier suggested that the variation of the axis is due only to the combination of the three different radii of curvature of the trochlea tali. The fact that the ankle joint possesses two different axes for dorsiflexion and plantarflexion has been supported by some later studies[2, 176].

The concept of instantaneous center of rotation was first introduced by Dempster[34]. He used X-ray sagittal pictures of several ankle flexion positions and the estimation method proposed by Reuleaux[130] in 1875, to show that the series of the instantaneous centers of rotation falls within quite a large area on the body of the talus. Following this preliminary study, other authors showed the changing positions of the center of rotation using sagittal exposures of the subjects in different ankle positions[33, 114, 125, 138, 140, 151,]. Most recent papers[13, 14, 43, 90, 96, 97, 124, 154, 166, 171], using more accurate techniques capable of detecting even small three-dimensional (3D) movement of targets, have generally reported that the axis of rotation of the ankle is not fixed but shows continuous changes throughout the entire range of motion. Rasmussen[124] described a continuous change of the axis during rotatory movements produced by externally imposed torque. Van Langelaan[171] measured tarsal bone positions and also found a moving axis of rotation even during external tibial rotation. Siegler et al.[154] collected calcaneus and talus position data from fresh amputated lower limbs using 3D sonic tracker. The observed non-linear coupling between the three components of the angular joint motions at the ankle proved that a single fixed axis of rotation is inappropriate to describe ankle joint motion. Lundberg[95] used accurate roentgen stereophotogrammetry in eight volunteers. The helical axis was calculated for six successive ankle rotations and projected onto sagittal, frontal and transverse planes. Their results clearly show the changing position of the axis, but also support the findings of Barnett and Napier[8] and Hicks[60] of two distinct patterns of motion about two different axes, one in the region of plantarflexion and one in the region of dorsiflexion. Even though many authors described a moving axis of rotation, no explanation of the changes in direction and in position was offered, a random movement of the joint being unlikely.

Several further studies have recently shown changing orientations of the instantaneous axis of rotation, although comparison of the results is made difficult by inconsistency between studies in defining the anatomical reference systems used. Thoma et al.[166] investigated the relationship between the movements in the ankle joint and the geometry of the lateral ligaments using digitized X-ray pictures. They pointed out that a hinge-like model was not able to describe the motion observed. Murphy[106] investigated the 3D kinematics of the normal unloaded ankle and subtalar joints using both bone-inserted and skin-mounted markers. The results obtained from both the bone and skin markers confirmed the movement of the axis. More recent studies[13, 14, 89, 90] have now measured the motion of the ankle axis of rotation even during passive flexion, when joint motion is constrained only by the articular surfaces and the ligaments. Although the inclination of the mean axis of rotation was found very similar to the single hinge axis reported by the pioneer studies[67, 68], the change in orientation of the axis in the frontal as well as in the horizontal planes was demonstrated.

Anteroposterior translations of the instantaneous axis of rotation were reported by only few authors. Sammarco et al.[140] claimed a large area for the positions of the instantaneous centre in their sagittal study of ankle rotations, but did not show any definite and reproducible path. Parlasca et al.[114] simply reported a circular area of 12 mm radius in which 96% of the calculated instant centers fell. Siegler et al.[154] found 9 mm of anteroposterior translation of the calcaneus during ankle rotation from maximal plantarflexion to maximal dorsiflexion. A mean antero-posterior and vertical displace-ment of the center of rotation in the sagittal plane of 10.2 and 10.6 mm respectively was also reported by these authors[89].

In conclusion, it has been recognized[141,142] that, although the Inman hinge model has the virtue of simplicity for an intuitive preliminary understanding of ankle motion, more accurate models require a moving axis of rotation, because angular motions are always accompanied by translational motions which uniaxial models make no attempt to describe.

5 JOINT PASSIVE STABILITY

Both the ligamentous supports and the articular geometry contribute to ankle stability. The contribution of bony geometry to joint stability depends on the degree of compression load applied and on the position of the ankle joint[46]. A dorsiflexed ankle was found to be more resistant to internal rotation than external rotation and the opposite was found in maximal plantarflexion. It was found[164] that, in the loaded state, articular geometry accounted for 30 and 100% respectively of the transverse and frontal plane stability.

5.1 Antero-posterior stability

The anterior drawer test is the most common technique for the clinical examination of the antero-posterior stability. It is often clinically interpreted as a sign of rupture of the ATF ligament[16, 55, 120], where other studies have found the examination to be unreliable, because a drawer sign can also be produced on an intact ankle[81, 123]. Several cadaver studies have characterized displacement of the ankle and demonstrated that sectioning of the ATF produces a significant increase in displacement. The load-displacement response is also nonlinear[70, 154]. The values of anterior-posterior translation in intact ankles have been reported to range between 1.5 and more than 9 mm[55, 85] mostly depending upon the external force used to induce the movement.

5.2 Flexibility/Stiffness characteristics of the joint

The load-displacement and flexibility characteristics of human joints can elucidate the joint response to externally applied forces and moments. Using the experimental 'flexibility' method, forces and moments are controlled and applied across the joint and the resulting displacements produced are measured. This method has been largely used in ankle joint investigations[24, 26, 70, 120, 124, 168]. The joint response to external loads is determined by the geometry and the mechanical properties of the cartilaginous and ligamentous structures. Their individual contributions to the stiffness or flexibility of the joint have been traditionally studied by sequential sectioning of the main ligamentous structures[26, 70, 155].

Siegler, Chen, and Schneck[26,155,156,157] conducted the most extensive investigation on the flexibility/stiffness characteristics of the ankle joint. In the former paper, they used pneumatic actuators to apply incrementally increasing pure moments to the calcaneus. Highly nonlinear load-displacement characteristics were found. They also determined the effects of the ATF sectioning on these characteristics, obtaining no significant variations in the load-displacement and flexibility characteristics in the sagittal plane, and only pronounced contributions in the transverse and frontal planes near the extremes of the range of motion. In intact specimens, they found significant resistance to DP moments, in contrast to the work by the authors[90] who argued that flexion could be accomplished in the presence of minimum load and who deduced that the unloaded joint allows flexion without significant tissue deformation. In the later paper[155], they compared 3D load-displacement and flexibility characteristics of the ankle joint prior to and following sectioning of the PTaF, CF, and ATF, in order to detect possible strong correlations between flexibility characteristics and isolated damage to the lateral collateral ligaments. They showed, as expected, a significant increase in the range of motion of the joint in all the three principal directions after sectioning of each ligament.

The diagnosis of the site and extent of ankle ligament injuries is based on direct findings from the history of the injury and from physical and radiographic evaluations. Some of the most common procedures include the inversion stress test, the anterior drawer test, and radiographic measurements of the amount of talar tilt[35, 84, 131, 135]. These clinical procedures are primarily qualitative in nature and do not provide conclusive indications of the site and extent of the ligament injury. Recently, Siegler et al.[156, 157] have developed a 6 degrees-of-freedom instrumented linkage to measure the 3D kinematics and laxity characteristics of the ankle complex. This allowed an operator to apply forces and/or moments across the complex and to measure the resulting motion. The linkage may be suitable as a diagnostic tool of ankle ligament injuries.

6. CONCLUSIONS

The ankle joint has been extensively investigated both in *in-vivo* and *in-vitro* studies, producing a huge series of experimental observations. However, the development of relevant elucidating models has not shown corresponding satisfactory results, making difficult the interpretation of these isolated and sometime contrasting series of data. Many critical important issues, such as multiaxial joint rotation, changing in contact area position, near-isometric pattern of rotation of certain ligament fibers, incomplete congruency of articular surfaces still need to be more deeply investigated and relevant results interpreted.

However, some of the observations from the literature summarized in this review seem to be qualitatively consistent. Several studies have described a more isometric pattern of rotation for the CF and the TC with respect to all the others. Several recent papers, using accurate methods of measurement, have also found changing positions of the instantaneous axis of rotation, suggesting that the hinge joint concept is an oversimplification for the ankle joint and does not reflect the real kinematic pattern. A few recent studies are also claiming anterior shift of the contact area at the tibial mortise during dorsiflexion. Recent papers from the authors have demonstrated that the complex pattern of motion is guided by the close relationship between the geometry of the ligaments and the shapes of the articular surfaces of the ankle. The slackening and the tightening of the ankle ligaments may be explained in terms of their instantaneous position with respect to the moving axis of rotation.

The relevance of this finding on the complementary role of ligaments and articular surfaces in the clinical practice is evident. Passive joint mobility mainly depends on the geometry of ligaments and articular surfaces. Geometrical changes to the structures that guide joint motion would affect the coupled motion observed in the intact joint. Any surgical treatment of the ankle complex should therefore be aimed first at restoration of this original geometrical relationship. The effects of changes to the original geometry of the intact joint, such as erosion of the articular surfaces, ligament injury and reconstruction, or total joint arthroplasty should be predicted by appropriate mathematical models. All this evidence also suggests that careful reconstruction of the original geometry of the ligaments is necessary after injury or during total ankle replacement.

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