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The relation between geometry and function of the ankle joint complex: a biomechanical review

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Abstract This review deals with the relation between the anatomy and function of the ankle joint complex. The questions addressed are how high do the forces in the ankle joint get, where can the joints go (range of motion) and where do they go during walking and running. Finally the role of the ligaments and the articular surfaces is discussed, i.e. how does it happen. The magnitude of the loads on the ankle joint complex are primarily determined by muscle activity and can be as high as four times the body weight during walking. For the maximal range of motion, plantar and dorsiflexion occurs in the talocrural joint and marginally at the subtalar joint. In-eversion takes place at both levels. The functional range of motion is well within the limits of the maximal range of motion. The ligaments do not contribute to the forces for the functional range of motion but determine the maximal range of motion together with the articular surfaces. The geometry of the articular surfaces primarily determines the kinematics. Clinical studies must include these anatomical aspects to better understand the mechanism of injury, recovery, and interventions. Models can elucidate the mechanism by which the anatomy relates to the function. The relation between the anatomy and mechanical properties of the joint structures and joint function should be considered for diagnosis and treatment of ankle joint pathology.

Keywords Ankle joint · Ligaments · Articular surface · Range of motion · Biomechanics

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Introduction

The biomechanics of the ankle joint complex (AJC) has been the subject of numerous studies. This seems warranted, since there is a large incidence of injuries of the AJC and the AJC is of great importance in normal ambulation, sports, and daily activities. The AJC comprises anatomical structures that actively and/or passively contribute to the function of the AJC. Although the anatomy was described in detail, the quantification of function and its relation with anatomy, also referred to as functional anatomy, is sparsely described in previous reviews [12, 16, 36, 41, 48, 52–54, 60, 69]. This review aims to address the function of the AJC in terms of loading and motion in relation to the joint's anatomy, more specifically, the role of the passive structures, i.e. the ligaments and articular surfaces.

The issues addressed in this review are the forces acting on the joint, the range of motion, joint function during activities and their relation with anatomy. With respect to the forces, the question is how high can it get? For the range of motion, where can it go? For function where does it go? For the anatomy, how does it happen? The loads on the AJC during daily activities are evaluated. It will be demonstrated what the mechanism is that determines the magnitude of the forces on the AJC. The maximum ranges of motion of the AJC are reviewed with discrimination between the talocrural joint (TCJ) and subtalar joint (STJ) and related to what is required for normal activities. Finally, some aspects of the relations between function and anatomy are reviewed.

Loads: how high can it get?

Simple biomechanical models of the ankle and foot can give realistic but generalized estimates of the magnitude of the forces acting on the ankle joint complex [38, 79, 89]. These models use a free body diagram (e.g. Fig. 1), that includes only a few of all load bearing structures.

The example model represents the end of the stance phase during walking or the stance phase in stair climbing (Fig. 1). Included are the ground reaction force F_{gr}, the force in the TCJ joint F_j and the forces in the Achilles tendon F_{at}. Assuming static equilibrium, the Achilles tendon force F_{at} with known ground reaction force F_{gr} follows from the moment equilibrium.

$$F_{at}a = F_{gr}b \quad (1a)$$

$$F_{at} = F_{gr}b/a \quad (1b)$$

If the angles α and γ of the force vectors with the vertical are small, then the joint contact forces F_j approximately equals the sum of the ground reaction force F_{gr} and the Achilles tendon forces F_{at}:

$$F_j \cong F_{at} + F_{gr} \quad (2a)$$

$$F_j \cong (b/a)F_{gr} + F_{gr} \quad (2b)$$

The Achilles tendon force is greater than the ground reaction force. It can be drastically amplified by the ratio (b/a) of the lever arm of the ground reaction force and lever arm of the tendon force. This is usually the case in the end of the stance phase in walking and stair ascend. For example a F_{gr} of about 1 body weight (BW), a F_{at} lever arm of 5 cm and a F_{gr} lever arm of 15 cm will result in a F_{at} of 3 BW and a F_j of 4 BW. If cocontraction of the antagonist muscles is present, then the joint contact force will be higher [61]. The Achilles tendon force was reported to be as high as 12.5 BW during jumping [40].

The model described above reflects the approach used by Stauffer et al. [79] and Walker [89]. Procter and Paul [62] incorporated more muscles in their model. Besides the TCJ, also the STJ and talocalcaneonavicular joint were included in the analysis. A mean peak force for the TCJ of 3.9 BW (2.9–4.7 BW range) was reported for the stance phase of gait. This is somewhat smaller than was reported by Brewster et al. [11] (4.5–5.0 BW). For the STJ and talocalcaneonavicular joint loads were 2.43 BW mean (1.6–3.1 BW range) and 2.8 BW mean (2.3–3.4 BW range), respectively [62]. At the beginning of the stance phase, AJC loads are lower because of the small moment arm of the ground reaction force.

In the TCJ, the load during the stance phase of gait is primarily carried by the articular contact between talus and tibial plafond, about 98% of the load for the remainder by the lateral (2%) and medial (0.01%) facets, as evaluated in a mathematical model using a discrete element analysis [29].

In conclusion, muscle function is the primary determinant for the magnitude of the loads acting on the AJC. The lever arm of the ground reaction force will be the largest during the end of the stance phase and the peak force will be about 4 times the body weight during normal walking.

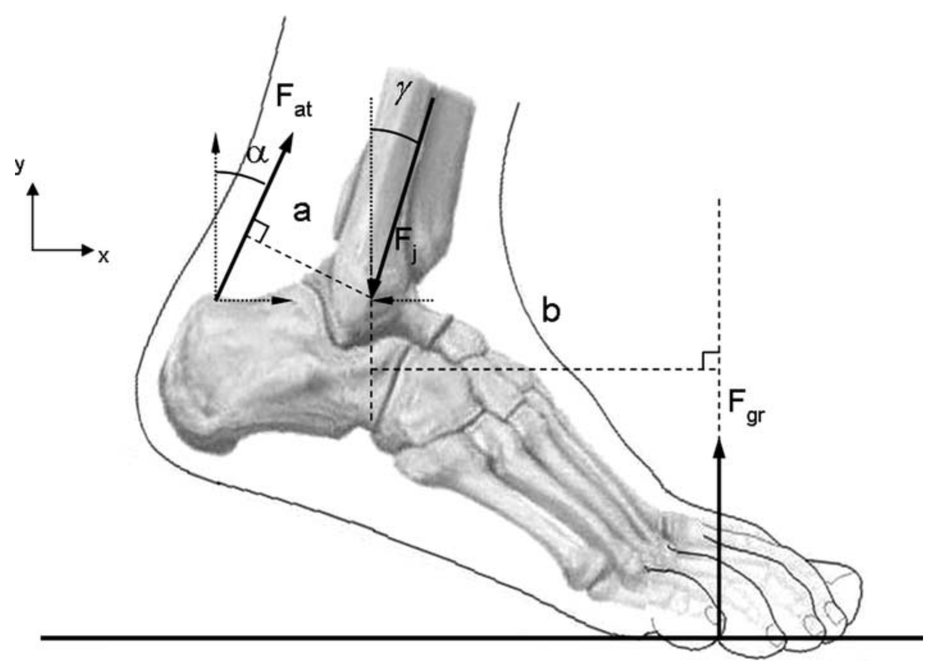

Fig. 1 A simple biomechanical model of the foot and ankle for determining the forces acting on the talocrural joint. F_{at} is the Achilles tendon force, F_j the joint contact force and F_{gr} the ground reaction force. Angles α and γ represent the angles of the force vectors with the direction of the given y-axis. (Figure adapted from Atlas of Anatomy, General Anatomy and Muscluloskeletal System, Thieme, New York, with permission)

Ranges of motion: where can it go and where does it go?

Even with high loads, the AJC can move with little effort in plantar-dorsiflexion and in-eversion. If diagnosing and treating the instable or the arthritic ankle, attention must be paid to the maximal range of motion (MROM) of the AJC in relation to the functional range of motion (FROM). Although clinically the motion of the AJC is relatively easy to assess, the distinction between the TCJ and the STJ is essential for proper diagnosis and treatment.

Different techniques were used to measure the kinematics of the AJC in vivo and in vitro. Optoelectronic systems that track surface mounted markers are easy to apply in vivo. They are not precise because of skin motion artefacts [14, 43, 65, 76, 92]. As the talus can not be tracked, the data are limited to motions of the calcaneus relative to the tibia.

An alternative is the use of markers attached to the bone, allowing also the talus to be measured. By placing tantalum markers in the bones in combination with roentgen stereophotogrammetric analysis (RSA), Lundberg [44] was able to determine the 3D positions and orientations of the ankle bones in different joint positions. Another invasive technique is the insertion of intracortical bone pins with markers which was used in vivo [1, 2, 45, 65, 92] and in vitro [3, 5, 25, 28, 31, 33, 37, 55, 57, 68, 72]. These studies have the advantage over the RSA technique in that the measurements can be performed while the joints moves dynamically.

Imaging techniques, such as magnetic resonance imaging [19, 20, 27, 47, 67, 70, 74, 80, 93] and computed tomography [8, 32, 88] were used to measure the extremes of motion or the kinematics during specific functions.

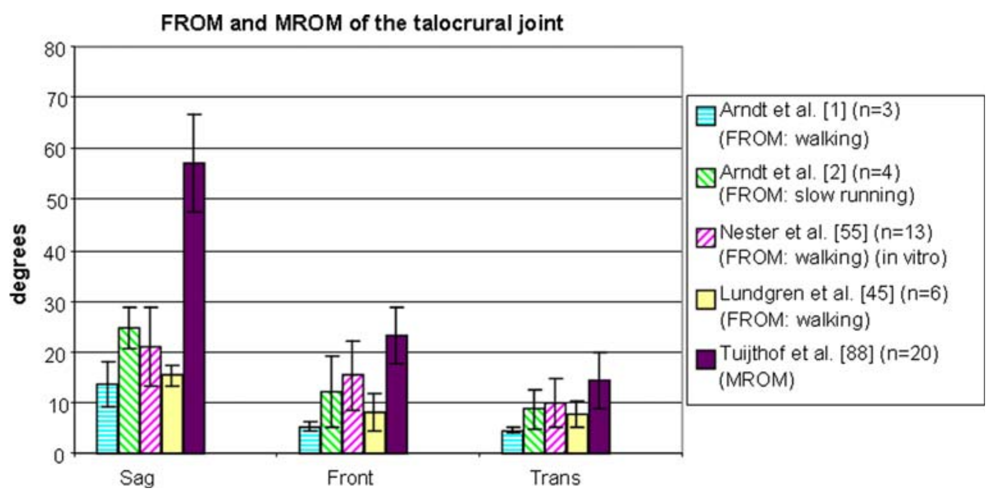

Fig. 2 MROM [88] and FROM [1, 2, 45, 55] of the TCJ. *Sag* sagittal plane (dorsi- and plantarflexion), *Front* frontal plane (eversion and inversion), *Trans* transversal plane (internal and external rotation). *Bars* represent the different studies. *Error bars* represent ± one standard deviation

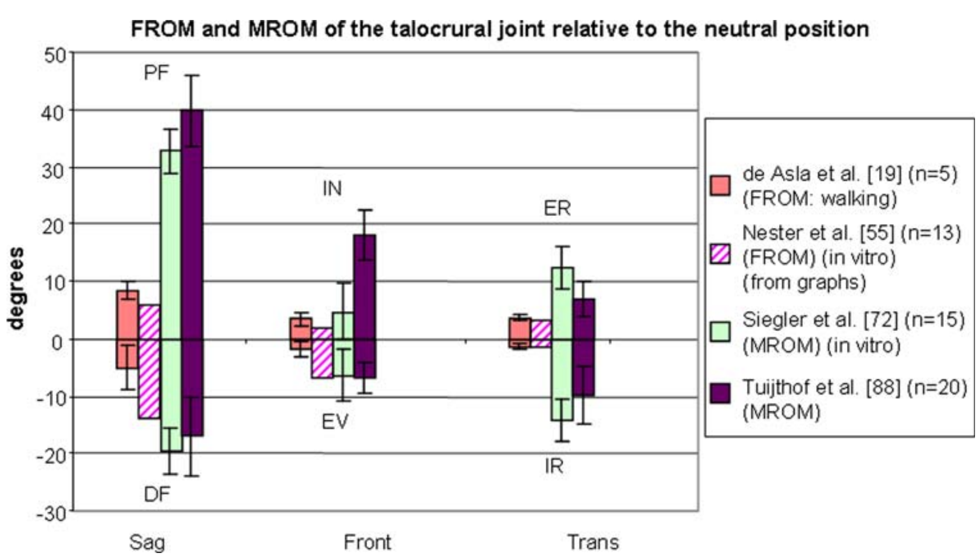

Fig. 3 FROM [19, 55] and MROM [72, 88] of the TCJ. *DF* dorsiflexion, *PF* plantarflexion (*sagittal plane*). *EV* eversion, *IN* inversion (*frontal plane*). *IR* internal rotation, *ER* external rotation (*transversal plane*). 0 degrees correspond to the neutral position. *Bars* represent the different studies. *Error bars* represent ± one standard deviation

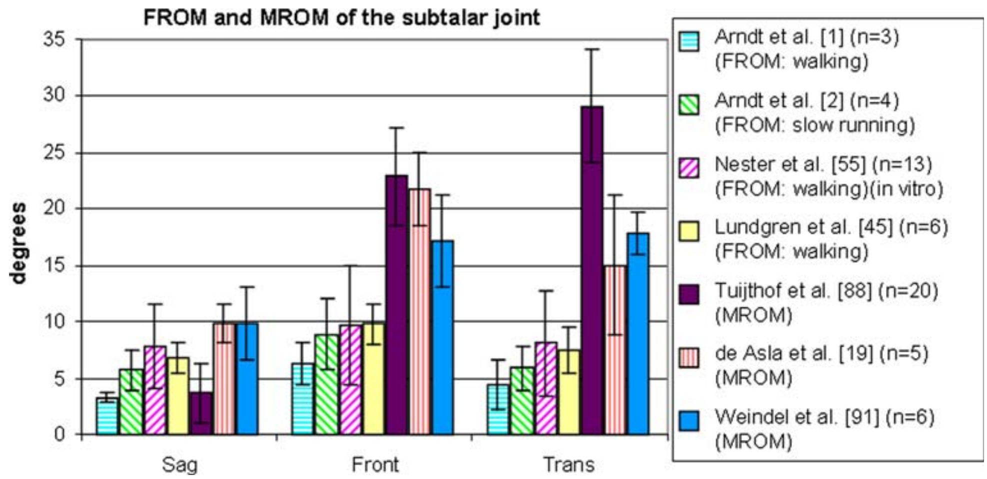

Fig. 4 FROM [1, 2, 45, 55] and MROM [19, 88, 91] of the STJ. *Sag* sagittal plane (dorsi- and plantarflexion), *Front* frontal plane (eversion and inversion), *Trans* transversal plane (internal and external rotation). *Bars* represent the different studies. *Error bars* represent ± one standard deviation

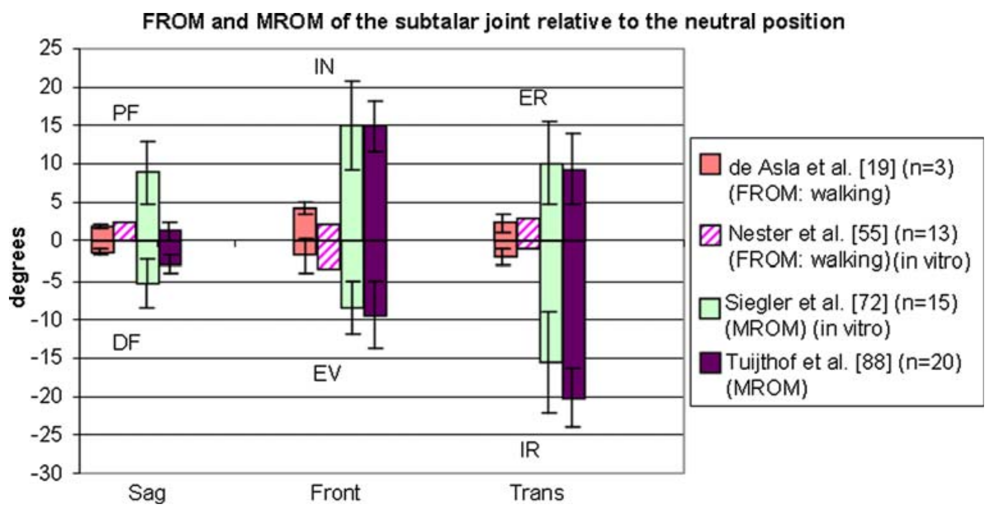

Fig. 5 FROM [19, 55] and MROM [72, 88] of the STJ. *DF* dorsiflexion, *PF* plantarflexion (*sagittal plane*). *EV* eversion, *IN* inversion (*frontal plane*). *IR* internal rotation, *ER* external rotation. *Bars* represent the different studies. *Error bars* represent ± one standard deviation

Here, the results from the various studies that measured either the MROM or the FROM are reviewed and summarized (Figs. 2, 3, 4, 5). The MROM is the maximal possible range without damaging any joint structure. The FROM in these studies is the range of motion measured during walking or running on even ground. Only those studies were included that reported the rotations in all anatomical planes, i.e. where a rotation is resolved into component rotation about three anatomical axes. Simultaneous motion in more than one anatomical direction within a joint is named coupled motion, whereas combined motion is composed of similar motion components that occur simultaneously in the TCJ and the STJ [88].

Dorsi-plantarflexion in the talocrural joint

The total MROM from dorsiflexion to plantarflexion in the TCJ in the sagittal plane is about 57 degrees (±10 deg. SD) [88] (Fig. 2). As the rotation axis of the TCJ is oblique relative to the anatomical planes, there are coupled rotations in the frontal and transverse plane. For walking and running the FROM is variable among studies, but much smaller than the MROM (Fig. 2).

Relative to the neutral position, i.e. the foot in the sagittal plane at 90 degrees relative to the tibia, the MROM for plantarflexion is about twice that for dorsiflexion [72, 88] (Fig. 3). During walking the FROM takes up a large portion of the MROM for dorsiflexion but a small portion of the MROM for plantarflexion (Fig. 3).

The differences between the studies can be explained by differences in the methods applied. Furthermore, the definition of the coordinate system has an effect on the resulting rotation components [10]. Tuijthof et al. [88] defined a coordinate system based on the anatomical axis of the talus, whereas others used a reference system based on foot anatomy.

In-eversion of the subtalar joint

The reported total MROM from eversion to inversion in the STJ in the frontal plane ranges between about 17 degrees (±4 deg. SD) [91] to 23 degrees (±4 deg. SD) [88]

(Fig. 4). Because of the anatomy of the STJ inversion is coupled to internal rotation and eversion is coupled to external rotation [42, 72, 88]. As the articular facets of the STJ have a vertical aspect [6, 69], there is marginal plantar and dorsiflexion [88].

For walking and running the FROM in the frontal and transverse plane is variable but much smaller than the MROM. The MROM and FROM in the sagittal plane is also variable but the differences between the MROM and FROM is less. Since the sagittal motion in the STJ is marginal this difference is expected to be smaller.

Relative to the neutral position the MROM for inversion is about equal to eversion [72, 88] (Fig. 5). During walking the FROM takes up a small portion of the MROM (Fig. 5).

The reported FROM for in-eversion of the STJ are rather small. This might be because the walking activity was on even ground. The role of the STJ has been described to be responsible for accommodation to uneven ground [12, 19, 46, 48]. Higher values of in-eversion are to be expected if the foot is placed on uneven grounds [e.g. 27].

Motion at two levels

The motion of the AJC is the combination of motion at two levels. Flexion is primarily at the level of the TCJ, with little or no motion in the STJ [88]. The MROM for in-eversion is reported to occur as a combined motion in both joints [88], whereby approximately two-third is at the level of the STJ and one-third at the level of the TCJ. The general orientation of the two rotational axes leads to coupling of inversion to internal rotation and eversion to external rotation in both joints [42, 72, 88].

The motion within the limits of the MROM was also described to occur within the so-called neutral zone, where the moment required to rotate the joints is small [17, 59, 90]. The implication is that muscle forces and muscle coordination are required to stabilize the joints during activities.

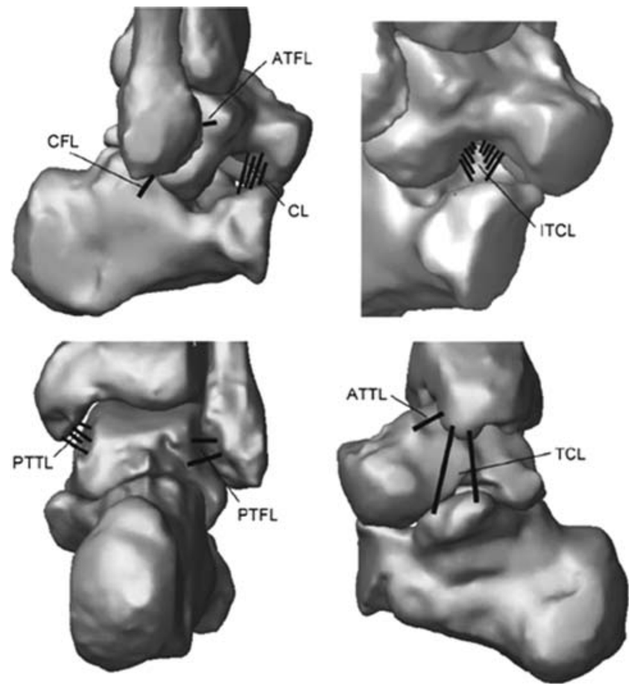

Fig. 6 A 3D representation of the specimen specific model of an ankle joint used in the study of Imhauser et al. [33] to predict the forced inversion range of motion and anterior drawer translation with experimentally determined values (Reproduced with permission)

Relation between geometry and function: how does it happen?

It can be hypothesized that the morphology of the joint complex, i.e. geometry of articular surfaces and of the ligaments, is the primary determinant of the MROM and the kinematics for the FROM [22]. This is, to some extent

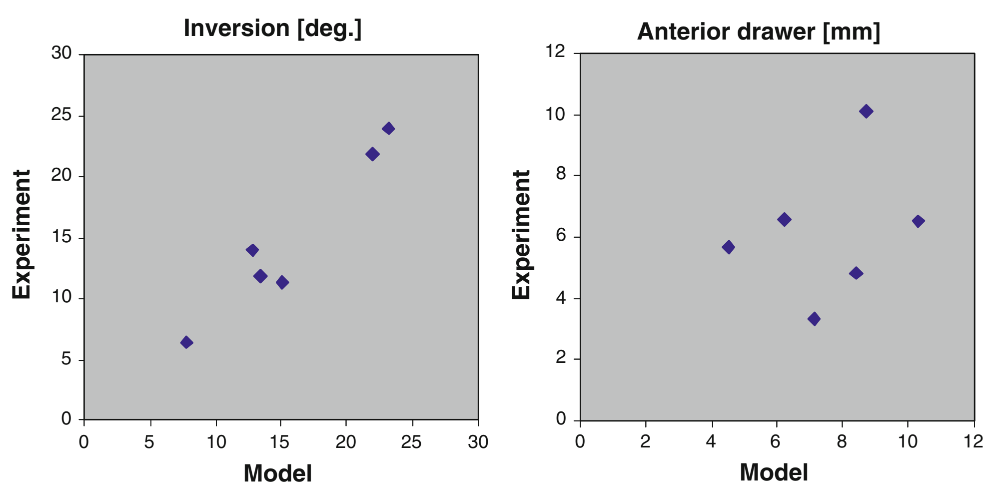

Fig. 7 Scatter diagram of the one-to-one comparison between model predictions and the corresponding experimentally determined forced inversion (3.4 Nm) and forced anterior drawer (150 N) in 6 ankle joint specimens in the study of Imhauser et al. [33]

supported, by Imhauser et al. [33] who made models of the AJC of six specimens based on morphological data obtained by MR images (Fig. 6). The mechanical properties of cartilage and ligaments were the same for all models and were estimated from literature data. Forced inversion (3.4 Nm) and forced anterior drawer (150 N) were compared between the specimen-specific model and the experiment on the specimen (Fig. 7). Apparently, for inversion more than for anterior drawer, the maximum range is determined by geometric differences. If extrapolating this, geometrical differences between subjects may explain differences in MROM and FROM of the AJC between subjects. Secondary to the geometry, the stiffness of the ligaments determines the stiffness of the joint at the limits of the MROM and the stiffness of the cartilage determines the contact area and stresses and strains in the articular contact.

In extension to the results of Imhauser et al. [33], the function of ligaments and articular surfaces are further discussed.

Ligaments

The main ligaments of the AJC are the laterally situated anterior talofibular (ATFL), calcaneofibular (CFL), and posterior talofibular ligament (PTFL) and the medially situated deltoid ligament. Ligaments between the talus and calcaneus (e.g. interosseous talocalcaneal and posterior talocalcaneal ligament) are beyond the scope of this review.

The function of the ankle joint ligaments is thought to control and limit the motions between the bones that comprise one or more joints. Many studies have shown that the ankle ligaments determine the MROM. Usually this was demonstrated by in vitro experiments where the effect is measured of ligament dissection on the MROM [e.g. 24, 39, 64, 81, 84].

The ATFL restrains inversion and anterior talar translation at all positions of flexion [41]. The CFL limits inversion together with the ATFL in plantarflexion and neutral position, and together with the PTFL in dorsiflexion [64]. The PTFL restraints external rotation in dorsiflexion [64].

The deltoid ligament is a large fan-shaped ligament originating from the medial malleolus. Because of the many variations and different insertions, it is difficult to discuss the function of the deltoid ligament as a whole. The most frequently reported function is the restraint against eversion [41].

Alternatives to cutting experiments are measurements of ligament length [20, 46, 77], strain [13, 15, 18, 56, 58, 66] or force [5, 15, 56, 71]. Data on ligament forces are scarce, but give some clue as to the function in controlling and restraining ankle joint motion [5, 9, 15, 56, 71]. The interpretation of the data on ligament length or strain as function of joint motion is hampered by the problem of defining the zero-load length of the ligaments. So is ligament strain, which is defined as

$$\varepsilon = [(L - L_0)/L_0] \tag{3}$$

where ε is the strain, L the current length and L_0 the zero-load length. The length of a ligament is a function of the distance between its origin and insertion and is thus a function of the relative motion between the bones. A strain smaller than zero means that a ligament is slack and does not function. Only ligament strains greater than zero result in a force in the ligament.

Studies that used a reference length that is equal to the length in the neutral position of the AJC, usually with the foot in 90 degrees relative to the tibia, report relative length changes with joint motion for which it is not clear whether ligaments are actually tensioned [e.g. 15, 18, 66, 73].

There are few studies that address the determination of the zero-load length and report estimates of the strain in ankle ligaments [26, 56, 58, 85]. These studies show that not all ligaments are taut in the neutral position of the ankle. Ozeki et al. [58] reported zero-load lengths of the four major ankle ligaments and also reported joint positions in dorsal-plantar flexion for the transition from slack to taut (Table 1).

The finding that the reported ankle ligaments are slack for neutral joint position and taut after a certain level of plantar or dorsiflexion, is in agreement with earlier findings of Nigg et al. [56] and Bahr et al. [5]. The latter showed that in a range of 10 degrees of dorsiflexion and 20 degrees of plantarflexion the force in the ATFL and CFL are zero or very small.

Studies that evaluated ligament function during walking confirm that the four ankle ligaments are slack [29, 85]. So within the FROM the ligaments are slack and towards the MROM they are tensioned [85]. Because of the low

Table 1 Zero-load length L_0 (in mm) of the ankle ligaments derived from Ozeki et al. [58] and the joint position for the transition between slack and taut

	L_0 (mm)	Joint position at slack-taut transition
ATFL	20.4	16.2 ± 2.6° PF
CFL	24.6	17.2 ± 6.4° DF
PTFL	30.5	18.0 ± 7.5° DF
TCL	27.4	9.5 ± 8.9° PF

ATFL anterior talofibular ligament, *CFL* calcaneofibular ligament, *PTFL* posterior talofibular ligament, *TCL* tibiocalcaneal ligament. The following abbreviations indicate the motion direction for which the ligaments becomes taut: *DF* dorsiflexion, *PF* plantarflexion stiffness of ligaments for small strains [4, 13, 26, 73] and the small moment arms, it questionable that the ligaments play an important role in guiding and limiting joint motion for normal functional activities. Also, the maximal forces in the ligaments as reported in literature [5, 15, 18, 56, 66] during motion and in the extreme end of motion are rather small if compared to the tendon loads. However, at the extremes of joint motion, plantar-dorsiflexion and in-eversion, but also forced anterior drawer [36] the ligaments act as motion constraints jointly with the articular contact.

The ligament may have a sensory function, hypothesized as early as 1900 [63]. Mechanoreceptors are found not only in the AJC ligaments [49, 51, 83], but also in other joints and can control muscle activity [75, 83]. Assuming there is a proprioceptive role for ligaments, then damage or rupture will result in a loss of neurosensory information.

Articular contacts

As elaborated above, the ligaments of the AJC do not contribute to the mechanics of the TCJ and STJ within the FROM. Therefore, the mechanics are primarily determined by the geometry of the articulating surfaces [27, 29, 41, 69]. The TCJ and STJ are highly congruent joints with a total contact area of 1.5–9.4 cm^2 [41]. The geometry of the articulating surfaces determine the kinematics and stability of the joints. If contact is maintained, the TCJ and STJ appear to function as joints with one degree of freedom of motion [27]. However, towards the limits of motion and in functional stress tests, like forced anterior drawer or forced in or eversion, congruent contact is not maintained. The motion will then deviate from the normal kinematics within the MROM. The question here is how much evidence exist for the relation between articular contact geometry and the kinematics for the FROM and beyond that but within the MROM. The second question is how the articular contact geometry contributes to the stability of the joints for the extremes of motion and for stress tests.

If the TCJ is statically compressed than the restraint against dislocating torques is primarily provided by the articular surfaces [29, 81, 86, 90]. The reported contribution levels accounted for 100% [90] and 70% [86] of anterior/posterior stability, 100% [81] and 50% [86] of in-eversion stability, and 30% [81, 86] or 60% [90] of internal/external rotation stability. Tochigi et al. [86] did not include the talomalleolar articulation and this might explain the lower contribution percentages in in-eversion and anterior–posterior stability.

The ankle mortise comprises the tibia and fibula with both malleoli. The talus is thus tightly packed. There is considerable variation in the shape of the TCJ [21, 30, 78] and STJ [6] among subjects. The shape of the tibial plafond in combination with the curvature of the trochlea tali [7, 34] determines the stability in the anterior posterior direction [23, 35] and the varus tilt of the tibial plafond is related to chronic ankle instability [82]. In agreement with this finding is that a simulated fracture, by an osteotomy of the anterior part of the distal tibia results in an increased anterior laxity of the TCJ [87]. An altered joint geometry, such as after malunion of a fracture, can result in joint instability [50, 87]. Also, an additional joint contact, e.g. a Stieda process, can result in different kinematics [70]. Barbaix et al. [6] hypothesized a same contribution of the anatomy of the STJ and subtalar instability, but no literature was found to proof this.

Discussion

This review addressed four questions concerning the ankle joint complex. The first was on the loading of the joint. How high can it get? The second was on the MROM. Where can it go? This was followed by the FROM. Where does it go? Finally, the relation between function and morphology was addressed. How does it happen? The literature was reviewed, such that answers were obtained on the above questions and, where possible quantitative data was presented. The review was limited to addressing the above questions.

The load on the ankle joint is high, amounting to several times the body weight. The primary determinants of the magnitude of the joint contact force are the ground reaction force of the foot and the moment arm of this force. Literature data on joint loading show variability among subjects or joint specimens. This may be the effect of variable geometry, i.e. moment arms of the muscles, but also of differences in muscle coordination and cocontraction of antagonist muscles.

The MROM of the AJC, i.e. the calcaneus relative to the tibia is achieved by the ROM of the TCJ and the STJ. It can be concluded that dorsi and plantarflexion is only at the level of the TCJ, whereas in-eversion is both at the level of the STJ and TCJ. A great variability is present between individuals.

Quantitative data on the FROM at the level of the TCJ and the STJ are limited to simple activities like walking and running on even ground. This may have underestimated the FROM for in-eversion. At any rate, the FROM are well within the MROM of the joints.

The mechanics of the AJC is not only a function of the geometry, but also of the mechanical properties of the ligaments and articular surfaces. It appears however, that ligament and articular geometry are the primary determinants of the MROM and FROM. Cutting ligaments affects the MROM, but if intact, their stiffness only affects the stiffness at the limits of the MROM and not so much the

ROM itself. No or little contribution of the ligaments is to be expected for motion and loading within the MROM. Stability is then determined by the congruency of the articular surfaces and stabilizing function of the muscles.

Various studies have shown that differences in articular geometry may explain the differences in function and even differences in susceptibility to ligament injury. In the future, much more need to be uncovered in this regard. Studies should aim for including geometric characteristics of the joints that are studied to be correlated with functional measures. Advanced mechanical models may find the mechanisms that govern the relations between geometry and function.

The AJC is a passive mechanical system that connects the foot to the lower leg. The ankle joint complex has interactions with the mid and forefoot, both passively through articular contacts and ligaments and actively by the tendons crossing the ankle. Conversely, there is no passive mechanical interaction with the knee joint. So it is a simplification to describe the mechanics of the AJC in isolation, though many studies have done this. The interaction with the mid and forefoot is more relevant for the STJ than for the TCJ, but the function of the latter cannot be considered in isolation from the former, because of the ligaments that span both joints. So in this respect, the review is limited by not addressing explicitly the interactions with mid and forefoot.

The clinical consequences are diverse. For developing diagnostic and treatment techniques for ankle ligament injuries, the contributions came from the studies on ligament function at the extremes of the range of motion. However, ligament function during sports activities, strenuous exercises or for near accidents remains to be uncovered. This may give guidelines for ligament reconstruction and postoperative rehabilitation. More importantly, future diagnostic techniques and treatments should include subject specific parameters, preferably to be included in personalized models, that not only include the passive mechanics but also the function of the dynamic stabilizing function of the muscles. These are the scientific challenges.

Clinicians can use these results to better understand the joint contact force determining factors. The values of FROM and MROM are helpful in diagnosing and interventions such as arthrodesis and the clinician should take into account that during normal ambulation motion takes place at both levels. Also, the clinician must understand the function of ligaments, i.e. it is not a limiting structure in the FROM, because the ligaments do not contribute to the stability within the FROM. Ligament reconstruction should take into account the zero-slack length for it determines at which joint angles the ligament is tensed and contributes to the force balance.

Conclusion

During walking the maximal joint contact force is about four times the body weight. This value is reached at the end of the stance phase where the moment arm of the ground reaction force is high. There is large variability between subjects in both MROM and FROM. The motion in the sagittal plane is primarily the result of the TCJ, but in the frontal plane both joint levels contribute. There is evidence that the geometry of the articular surfaces determines the kinematics. Also the susceptibility to ankle injury might be explained in terms of AJC geometry. The ligaments are only restraining the motion near the MROM, so articular surfaces, alternatively in combination with muscle activity, must provide the stability within the FROM.

Conflict of interest statement The authors declare that they have no conflict of interest.

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