Ligament fibre recruitment and forces for the anterior drawer test at the human ankle joint

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Introduction
The anterior drawer test (ADT) is the most common clinical examination test of the ankle joint, aimed at determining the integrity of the ligaments. Very little is known about how ligament fibres are recruited and how the external anterior force is shared between the ligaments, thus the clinical interpretation of the test is still obscure. Contrasting indications are given on the most appropriate angle of dorsiflexion/plantarflexion (Do/Pl) at which the test should be performed. Most of the experimental studies reported in the literature lack an accurate reproducibility, and comparison is made difficult also by the different experimental conditions and different status of the specimens.

Theoretical studies for ADT have been valuable for the human knee joint. The findings of these studies encouraged the development of mathematical models of the ankle joint. A recent study (Leardini et al., 1999) showed the path of motion of the ankle joint in the unloaded state. The mechanical response of the ankle joint to external load is still to be investigated.

The objective of this work was to devise a mechanical model of the ADT at the ankle joint, aimed at representing the patterns of ligament fibre recruitment and at analysing the load sharing between the ligaments. The hypothesis of the present study is that during ADT the pattern of external load sharing and the force-displacement curve change significantly along the range of flexion, associated to the different initial ligament shape and orientation.

Methods
The starting point of the present study was a previous model of passive kinematics of the ankle joint (Leardini et al., 1999). In that investigation the ankle joint was modelled as a four-bar linkage in the sagittal plane, according to the nearly isometric pattern of rotation found for the anterior fibres of the Calcaneofibular and Tibiocalcaneal ligaments.

The present study was focused on the mechanical behaviour of the ankle joint under load. Ligaments were modelled as three-dimensional (3D) arrays of 10 fibres. Straight-line segments in space were used to represent ligament origin and insertion areas (Figure 1).

Figure 1: Antero-medial view of the three-dimensional model of the left ankle complex analysed.
The joint complex model included the eight ligaments which span the ankle complex joint: Anterior Talofibular (ATaFi), Posterior Talofibular (PTaFi), TiCa, CaFi, Tibionavicular (TiNa), Deep Anterior Tibiotalar (DATiTa), Deep Posterior Tibiotalar (DPTiTa), Superior Tibiotalar (STiTa). Ligament fibres were assumed to develop stress along their principal axis. A non-linear stress/strain relationship was assumed for ligament fibres. Stress $\sigma$ was modelled as a quadratic function of strain $\varepsilon$ for small deformations, and as a linear function for larger deformations. The geometrical arrangement of ligament attachment areas was taken from previous experimental studies from these authors. Two different data sets from the literature were used for the mechanical characteristics of ankle ligaments: data set $\Omega$, (Attarian et al., 1985) and data set $\Psi$, (Siegler et al., 1988). The articular surfaces of the tibial mortise and of the trochlea tali were taken as circular arcs in the sagittal plane.

During ADT, only the passive structures of the joint were supposed to resist the pulling action of the clinician. The tibia/fibula (Ti/Fi) complex was assumed to be rigid, to which the reference frame $xy$ was rigidly associated (Fig. 1). The talus and the calcaneus (Ta/Ca) were considered as a second rigid body. The ADT was analysed throughout the passive 20° Plantarflexion/20° Dorsiflexion range. Contact was assumed to be frictionless and to persist throughout the imposed ADT motion. As during ADT the flexion is maintained constant by the clinician, the pulling action was modelled as an anterior force which produces only an antero-distal translation to the Ta/Ca segment according to the shapes of the tibial mortise and trochlea tali. The calculation of the forces developed within the individual ligaments was performed by integrating fibre stress over the area on which stretched fibres insert along the ligament segments. Static equilibrium between external, ligament and contact forces was performed in the sagittal plane.

Results & Discussion

Figure 2 shows load/displacement curves for both data sets in five flexion positions.

![Figure 2: Force/displacement plots for five flexion angles (20°Pl, 10°Pl, neutral position, 10°Do, 20°Do).](image)

Figure 3 reports anterior displacement of Ta/Ca versus ankle flexion angle. Different ranges of forces were applied for data set $\Omega$ (5, 10, 15, 20N) and $\Psi$ (10, 20, 30, 40N).
Data sets $\Omega$ and $\Psi$ provided similar qualitative information about the mechanical response of the ankle joint. Response to ADT was found to get stiffer for increasing angles of Do and Pl (Figure 2 and 3). Load/displacement curves decreased in slope going from 20° Pl to neutral position, then got gradually steeper going from neutral position to 20° Do. Consequently (Figure 3) a given external force produced a maximum displacement about neutral position and smaller displacements closer to the extremes of the flexion range. Analysis of ligament load sharing confirmed the ATaFi ligament as the primary restraint to ADT motion at the ankle joint. This ligament was loaded by the largest amount of the external load throughout the range of flexion. The largest force supported was found at maximum Pl (39N with $\Omega$, 267N with $\Psi$), where most of its fibres were already just tight in the initial unloaded condition. The TiNa ligament responded to ADT only at Pl angles (at 20°Pl, 3.5N, 34N with $\Omega$, $\Psi$), the TiCa only at Do angles (at 20°Do, 4N, 7N with $\Omega$, $\Psi$). With data set $\Omega$, the DATiTa ligament shared an important portion of the external load throughout the flexion range (about 10%), whereas it barely stretched with data set $\Psi$. There is a qualitative good agreement between the present predictions and the experimental results from the literature, particularly on the dependence of the ankle stiffness to joint position. Bahr et al. (1997) reported an average anterior displacement of about 3.8, 4.4, 5.2 and 3.7 mm respectively at 20° and 10° Pl, neutral and 10° Do positions. Similarly, Bulucu et al. (1991) reported 6.0, 6.4 and 4.5 mm at 15° Pl, neutral, 15° Do positions. The ankle joint was confirmed to have maximum laxity at neutral position (Figure 2). The force/displacement behaviour from previous experimental studies are basically in between the two set of results ($\Omega$ and $\Psi$) here reported (Figure 2). The two main assumptions of the present model, i.e. rigidity of articular surfaces and pure elastic behaviour for the ligaments, are expected to overestimate the force at a given displacement. This mechanical model of the ankle joint provides a powerful and flexible tool for clinical applications. The clinician is given reference data to assess ankle response during manual ADT.

References