Tenodeses destroy the kinematic coupling of the ankle joint complex

A THREE-DIMENSIONAL IN VITRO ANALYSIS OF JOINT MOVEMENT

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To study the effect of ligament injuries and surgical repair we investigated the three-dimensional kinematics of the ankle joint complex and the talocural and the subtalar joints in seven fresh-frozen lower legs before and after sectioning and reconstruction of the ligaments. A foot movement simulator produced controlled torque in one plane of movement while allowing unconstrained movement in the remainder.

After testing the intact joint the measurements were repeated after simulation of ligament injuries by cutting the anterior talofibular and calcaneofibular ligaments. The tests were repeated after the Evans, Watson-Jones and Chrisman-Snook tenodeses. The range of movement (ROM) was measured using two goniometer systems which determined the relative movement between the tibia and talus (talocrural ROM) and between the talus and calcaneus (subtalar ROM).

Ligament lesions led to increased inversion and internal rotation, predominantly in the talocural joint. The reconstruction procedures reduced the movement in the ankle joint complex by reducing subtalar movement to a non-physiological level but did not correct the instability of the talocural joint.

Injuries to the lateral ankle ligaments are most common in young, active adults and account for many sports-related injuries. Acute ruptures are found most often in the anterior talofibular ligament (ATFL), followed by the calcaneofibular ligament (CFL) (usually in combination with the ATFL), and then the posterior talofibular ligament (PTFL). They can be treated conservatively or operatively with similar rates of success. Residual problems, described as chronic lateral instability of the ankle, have been found in 10% to 30% of patients. This condition includes a feeling of giving way, reduced range of movement, and pain and swelling after various degrees of loading. Patients report recurrent inversion injuries and have restriction of sport or daily activities. Those who do not benefit from physiotherapy such as neuromuscular and proprioceptive training need surgical reconstruction of the lateral ligaments to restore joint stability. Treatment varies from anatomical reconstruction to non-anatomical repair, and tenodeses which use the peroneus brevis tendon are popular; almost 80 procedures and modifications have been described. Subjective patient questionnaires usually give high rates of success, even although tenodeses are not strictly anatomical and therefore affect joint biomechanics. Clinical long-term follow-up studies have shown an impaired range of movement after certain types of tenodesis, which may partly explain the high rate of residual problems and the occurrence of advanced arthritis.

Various techniques have been described to determine the three-dimensional range of movement of the ankle joint complex in vivo, but they do not differentiate between movement in the separate joints. Recently, invasive in vivo measurements in the talocural and subtalar joints have been reported. Our study evaluated the three-dimensional kinematic characteristics of the ankle joint complex with intact, sectioned and reconstructed ligaments. We expected that the stability lost by sectioning ligaments would not be restored by tenodesis thereby causing non-physiological ankle movement. More specifically, we determined the degree of rotational instability in the ankle joint complex (AJC) and the talocural (TCJ) and subtalar (STJ) joints after serial sectioning of the anterior talofibular (ATFL) and the calcaneofibular ligaments (CFL), the influence of three popular types of tenodesis (Evans, Watson-Jones and Chrisman-Snook) on the range of movement of these joints and
the type of tenodesis which was most appropriate for restoring joint stability while retaining normal joint kinematics.

Materials and Methods

We used seven fresh-frozen lower legs from donors (three men, four women) with a mean age of 72 years. The specimens were frozen at –24°C until they were thawed at room temperature for 12 hours before the experiments. They were cut to a uniform length (13 cm above the malleoli) and soft tissue was removed down to the malleoli, taking care to preserve the ligaments of the ankle capsule and the peroneal tendons. The tissue was kept moist with saline solution throughout the experiment. The ends of the tibia and fibula and the plantar aspect of the calcaneus were embedded in a cylinder of polymethylmethacrylate (PMMA, Technovit; Kulzer, Wehrheim, Germany). Three cancellous screws through the calcaneus and the PMMA gave a stable connection to a flange which was connected to the gimbal of a load simulator.

A computer-controlled kinematic simulator allowed unconstrained movement in all translational and rotational directions thus providing six degrees of freedom. The simulator had been developed for testing the spine and was adapted to allow movement of the foot specimens with predetermined torques in each of the main rotational axes. The kinematic simulator consisted of a base mount with a travelling gantry. The core part was a gimbal (cardanic joint) with a mounting device for the specimens (Fig. 1). The gimbal allowed rotation around all three axes. The travelling gantry enabled movement to be made in the horizontal plane and also up and down, thus providing six degrees of freedom. The specimens were fixed upside-down with the tibia and fibula in the base mount and the calcaneus connected to the gimbal. Movements were induced by step motors integrated in the gimbal axes and connected by a clutch, thus controlling the x-, y- and z-axes. A predetermined and computer-controlled torque could be generated in one axis of rotation while the other directions were allowed to move unconstrained. A six-component load cell (Schunk; Lauffen/Neckar, Germany) measured the torques in plantar flexion/dorsiflexion ($M_x$), eversion/inversion ($M_y$) and external/internal rotation ($M_z$).

Movement in the talocrural and subtalar joints was measured using Schanz screws which were drilled into the posterior aspects of the tibia, talus and calcaneus. The relative movement of the TCJ was measured between the tibial and talar screws and that of the STJ between the talar and calcaneal screws with two three-dimensional potentiometer linkage systems. Each system consisted of six high-precision potentiometers (P1701A502; Novotechnik, Ostfildern, Germany) connected by aluminium bars. The accuracy of the system was determined as less than 3% for translations and rotations. The relative movement between the two solid bodies was calculated using projected angles. The values were continuously measured with a frequency of 20 Hz and stored on a computer.

A joint co-ordinate system was defined according to the recommendations of the International Society of Biomechanics, with three perpendicular planes (frontal, transverse and sagittal) with an origin in the approximate centre of the talus. The angle $\alpha$ described the movement in...

![Figure 1](image_url)
the sagittal plane, i.e. plantar flexion/dorsiflexion occurring around the x-axis defined as the mediolateral connection through the malleoli (Fig. 2). The angle $\beta$ described the eversion/inversion movement in the frontal plane and occurred around the y-axis aligned with the longitudinal axis of the foot through the centre of the heel and the second toe. External/internal rotation in the transverse plane around the z-axis (located in the centre of the talus and along the tibia) was described by the angle $\gamma$.

Predetermined torques were chosen for all specimens and conditions to allow direct comparisons. In a pilot study we determined the maximally permissible torques that were low enough to be harmless for the most unstable situation. Three loading cycles in the main directions of rotation (plantar flexion/dorsiflexion (PF/DF) with ±2.5 Nm; eversion/inversion (EV/IV) with ±2.5 Nm; external/internal rotation (ER/IR) with ±1.0 Nm) were used to assess the ankle joint complex when intact, after ATFL sectioning, after additional CFL sectioning, and after ligament reconstructions.

We performed the Evans procedure according to a modified technique described by Zwipp and Oestern. A split peroneus brevis tendon graft was used to fix the fibula by pulling the graft through an oblique drill hole of 30° from posterior to anterior and suturing it to itself close to the insertion in the base of the fifth metatarsal under a tension of 50 N. This tenodesis crossed both the TCJ and the STJ running between the anatomical direction of the sectioned ligaments (Fig. 3a). The Watson-Jones tenodesis simulated the ATFL by connecting the tendon graft to the talus after pulling it through the fibular drill hole. This was achieved by releasing the graft of the Evans tenodesis and fixing the tendon to the talus neck with a small screw (length 16 mm, diameter 3.5 mm) under a tension of 50 N (Fig. 3b). The Chrisman-Snook procedure used the peroneus brevis graft for reconstruction of the CFL. The graft was pulled through the fibular drill hole from anterior to posterior and fixed in the talus neck and the calcaneus at a tension of 50 N (Fig. 3c).

Two loading cycles were used to precondition the specimens and only the third cycle was used for analysis. The first cycle produced a slightly smaller range of movement whereas the second and third cycles produced almost identical patterns (Fig. 4). The maximum excursions in each of the rotational axes were determined and averaged across all specimens. Statistical comparisons between the intact and the experimental conditions were made using the Wilcoxon test with a significance level at $p < 0.05$.

Results

Owing to the complexity of the data the values measured in the injured or reconstructed conditions are reported as percentage changes with respect to the intact condition.

With intact ligaments the AJC achieved a maximal plantar flexion/dorsiflexion range of movement (ROM)
of 36.6° with a torque of ±2.5 Nm. The total ROM occurred predominantly in the TCJ with 31.3° ROM; the STJ was less involved with only 3.1°. Sectioning of the ATFL led to a significant increase (+5%, p = 0.02) in this plane of movement in the AJC, but only insignificant changes were seen in the other joint movements (Fig. 5). Sectioning of the CFL further increased the AJC ROM (+11%, p = 0.02). The Evans tenodesis did not reduce the plantar flexion/dorsiflexion ROM to the preinjury state (+8%, p = 0.02) and revealed an increased ROM in the talocrural joint (+12%, p = 0.02). The Watson-Jones procedure produced no significant changes in plantar flexion/dorsiflexion and led to a near normal restoration. The Chrisman-Snook technique also restored normal AJC and TCJ movement but gave reduced STJ ROM (−58%, p = 0.02).

In the frontal plane, the total ROM was 21.1° under a moment of ±2.5 Nm which mostly took place in the STJ (16.0°) with only 3.4° in the TCJ. The AJC movement increased by 6% (p = 0.03) after cutting the ATFL and by 28% (p = 0.02) after cutting the CFL (Fig. 6). These changes were seen mostly in the TCJ which showed increased ROM (+68% after ATFL section, +162% after CFL section). The STJ was not significantly affected. A decreased range of movement in the STJ was found after all three procedures (Evans: −31%, p = 0.02; Watson-Jones: −20%, p = 0.03; Chrisman-Snook: −53%, p = 0.02) although these changes were not reflected in the AJC, possibly because the TCJ range of movement was increased after all procedures (Evans: +97%, p = 0.02; Watson-Jones: +26%, not significant; Chrisman-Snook: +150%, not significant).

The total ROM in the transverse plane was 27.7° under a load of ±1 Nm and was evenly distributed between the TCJ (11.1°) and the STJ (12.3°) (Fig. 7). Ligament sections increased the AJC ROM by 18% after cutting the ATFL and by 32% after cutting the CFL. The TCJ was mainly affected
and increased the ROM by 59% and 86%, respectively. All three tenodeses reduced the AJC ROM to a level below the preinjury state (Evans: –13%, not significant; Watson-Jones: –27%, p = 0.02; Chrisman-Snook: –21%, p = 0.02). This was due to a decreased STJ ROM (Evans: –53%, p = 0.02; Watson-Jones: –27%, not significant; Chrisman-Snook: –63%, p = 0.02). The TCJ ROM increased after the Evans (+39%) and Chrisman-Snook procedures (28%).

Table I gives the results of the statistical tests. It can be seen that the increased overall joint instability after ligament lesions predominantly took place in the talocrural joint while the subtalar joint was not affected. The Watson-Jones procedure caused the least changes in joint kinematics whereas the Evans procedure markedly impaired joint movement in all directions.

**Discussion**

We have shown that ankle instability caused by sections of the ATFL and CFL mostly affects eversion/inversion and external/internal movements and is less reflected in plantar flexion/dorsiflexion. The instability occurred mainly in the TCJ and the findings do not support the view that subtalar instability is a consequence of lateral ligament injuries.

It was also shown that although the ligament reconstruction procedures provided stability in the ankle joint complex, the predominant reduction in range of movement was observed in the STJ. This must be seen as an overcorrection because instability in the TCJ was not eliminated.

A comparison of the three procedures showed that the Watson-Jones tenodesis achieves the best restoration of ankle stability with the least adverse effects. The modified Evans procedure did not control the increased movement in the TCJ but achieved overall ankle stability at the expense of an impaired range of movement in the STJ. The Chrisman-Snook procedure gave similar but less pronounced effects as the Evans procedure.

There are limitations to our experimental method. The specimens used were taken from elderly patients and may not have had the ranges of movement of normal younger subjects. Our aim was to study the changes in the ROM induced by ligament lesions and reconstructions and they should be independent of the initial conditions. We performed the experiments without an axial load; this was necessary in order not to jeopardise the integrity of the specimens, although it has previously been shown that axial loads can increase ankle stability. Our study investigated the unloaded situation which is realistic for an ankle immediately before a supination injury and thus appeared appropriate. Muscle activity was not simulated although the ankle is mainly stabilised by some of the strongest muscles in the human body. This limitation again was necessary to investigate the mechanical effect of the ligaments. It has been shown that the lateral ligaments can sustain maximum loads of only 200 N to 350 N and thus are too weak to withstand loads in the range of the body-weight. The main purpose of the ankle ligaments appears to be to provide guidance for the bones in the relaxed ankle in order to achieve a favourable position before the foot accepts body-weight during ground contact. A final limitation was the use of standard torques for all specimens in each condition. These had to be low enough to prevent unwanted damage to the specimens especially after sectioning the ligaments. Therefore, in the intact joints, the maximum possible ROM was not reached by the applied moments. This may explain the slightly lower values compared with those reported in the literature.

The changes which were observed after ligament transection agree with those in previous reports. Cutting the ATFL only primarily increased inversion and internal rotation and to a less extent plantar flexion. Further transection of the CFL increased ankle instability. Kjaersgaard-Andersen et al reported that a solitary lesion of the ATFL increased the anteroposterior laxity and caused minor internal rotational instability of the ankle. The additional CFL lesion led to a further increase in the anterior drawer (predominantly in dorsiflexion) and internal rotation. Siegler et al showed that different ligament injuries produced unique and identifiable changes in the flexibility

<table>
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<th>Plantar flexion/dorsiflexion</th>
<th>ATFL cut</th>
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*p < 0.05
characteristics of the ankle joint complex, without describing the relative involvement of the two separate joints.

The stabilising effect of the tenodeses induced a loss in ROM owing to the non-anatomical character of the reconstructions. These unwanted side-effects have been described by other authors who recommended procedures which mimic the anatomical orientation of the ligaments. 27-33 The kinematic coupling between the TCI and the STJ is disturbed after tenodesis. Altered joint kinematics eventually may lead to the accelerated joint degeneration that has been found as a long-term consequence.

The talus is not connected to a tendon and therefore is not directly controlled by muscle activity. In the Evans tenodesis there is no direct attachment and therefore it cannot directly control the anterior drawer and internal rotation tendency of the talus after ligament injury. The stabilising effect is achieved by pulling the tip of the fibula downwards and anteriorly to the base of the fifth metatarsal which may help to explain the reports of relatively high rates of residual instability. 7,8,36-39 This procedure should not be used before alternatives have been considered.

The Watson-Jones procedure was the best of the procedures with respect to fixation of the talus and also prevented impairment of subtalar movement. It may restore TCI stability in ATFL injuries but is not appropriate for treatment of subtalar instability.

The impairment in ROM was most pronounced in the Chrisman-Snook procedure which can almost be described as an arthrodesis in the STJ 10,41 because it leads to a direct coupling between the talus and calcaneus. Nevertheless, fairly high rates of patient satisfaction have been reported with this procedure. 39,42-46

The experimental results can well be transferred to the clinical situation. All three types of tenodesis led to a remarkable reduction of internal rotation and inversion in the ankle. Even although these restrictions were often not a source of great discomfort, it was noted that the clinical results deteriorated with time. In a recent study on intra-articular pressure measurements we found a significant increase in subtalar loading after tenodeses. 47

After more than 20 years Van der Rijt and Evans 48 noted several late failures in patients with initially stable Watson-Jones reconstructions. Long-term studies after the Evans tenodesis also showed results which deteriorated with time. 34,36 Snook et al 49 reviewed their reconstruction after more than ten years of follow-up. They confirmed a loss of 20° of inversion but did not report this as a problem. The clinical results show that the Evans tenodesis produces the worst results owing to the non-anatomical course of the tendon. 6,34,36,49 and that this is associated with subtalar arthritis in some patients after more than ten years. 9

The Chrisman-Snook reconstruction gives acceptable clinical results but it is suggested that there is a high incidence of sural nerve injuries. 36

Our studies have shown that a mechanical insufficiency of the lateral ankle ligaments can be described as an inversion and internal rotation instability. This has to be taken into account when considering treatment for restoration of lateral ankle stability while retaining a physiological range of movement. All of the reconstruction procedures investigated impaired the kinematic coupling of the ankle joint complex to some degree, but the least detrimental procedure is the Watson-Jones tenodesis. The Evans and Chrisman-Snook tenodeses do not appear to fulfil the requirements of treatment.

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References


