IN VITRO AND IN VIVO DETERMINATION OF ANKLE JOINT AND SUBTALAR JOINT AXES USING THE HELICAL AXIS METHOD

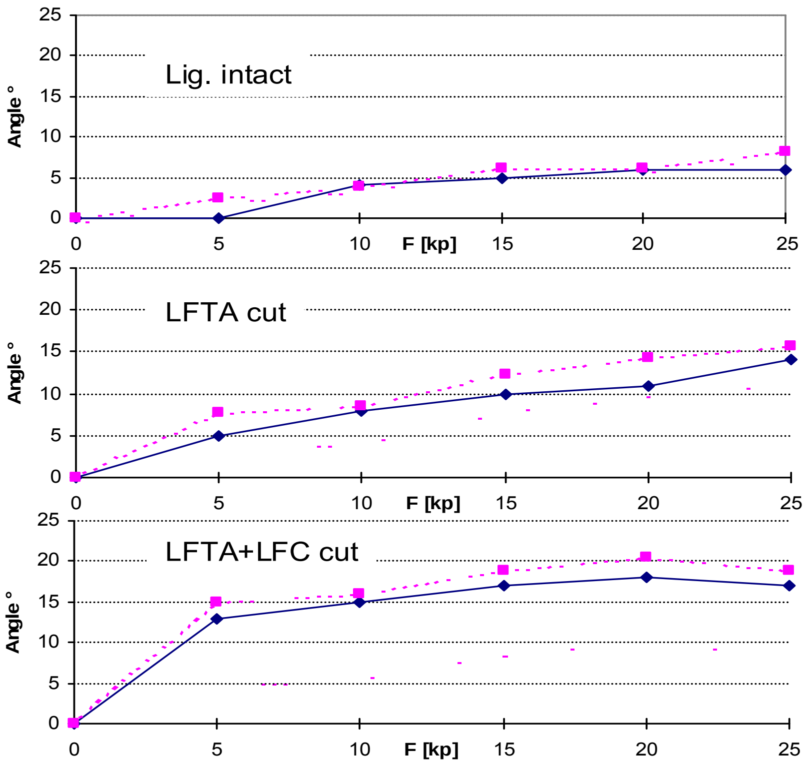
Wilfried Alt, Albert Gollhofer, Universität Stuttgart, Germany,
H. A. C. Jacob, Klinikum Balgrist, Zürich, Switzerland,
Heinz Lohrer, Bernd Rappe,
Sportmedizinisches Institut, Frankfurt, Germany

INTRODUCTION: Lateral ankle sprains are very common, especially in high risk sports like basketball, volleyball or soccer. In the literature it has been suggested that one potential reason for this incidence of injury might be sought in distinct structural characteristics of the foot architecture that may put some individuals at a greater risk of contracting injuries (12,13).
Injuries to the lateral ankle ligaments are most often accompanied by combined motion of plantar flexion and inversion. These motions are, in part, dependent upon the orientation of the axes of the ankle joint or talocrural joint axis (TCA) and the subtalar joint or talo navicular calcaneal joint (STA). On the other hand, the motion of the ankle and subtalar joints might be related to the orientation and strength of ligaments and capsular structures.
In the kinematic analysis of most human joints continuous motion can be simulated by a sequence of finite motion steps of one part of the joint relative to the other. Besides other methods, the general representation of a finite rigid body motion as a rotation about an axis and a translation along the same axis is known as the "screw" or the "helical" axis of motion (3, 4, 7).
Details of computational procedure were published by Kinzel (9) and, with the application of Rodrigues' formula, by Bishop (2).
Different experimental setups (2-D and 3-D x-ray or film analysis or modeling) were used in previous studies in vitro to determine STA, and great variability could be shown for both orientation and position of the joint axis (1, 5, 6, 8, 17, 18). The orientation of the axis can be described as a projection on anatomical planes in terms of deviation (the projection to the transversal plane) and as an inclination (the projection to the sagittal plane).
The average results of the most important previous studies (6, 11, 17, 18) are calculated for Inclination (40°) and Deviation (20°).
The study objective was to verify the application of the helical axis method to the ankle and subtalar joint in vitro and to extend that method for in vivo investigations.

METHODS: (I) In vitro: one fresh frozen ankle specimen from a 16-year-old female was thawed pre-experimentally and then fixed in a laboratory frame. The lower leg was fixed about 15 cm proximal to the ankle joint. In the first series we used stereo photogrammetry to determine optimal marker positions. Three markers were fixed (2 mm steel pins) to the talus and to the tibia respectively. In order to measure only motions in the subtalar joint two crossed 2 mm steel rods were used to fix the ankle joint. The joint was moved manually from eversion to inversion and from neutral position to inversion or eversion. The experimental procedure and calculation of coordinates is given in (7).

(II) In a second series with 2 right ankle specimens (67 and 72 years, male) a series of stress x-rays were used to compare talar tilt and the helical axis. The markers were fixed to the talus and tibia in the same position as described in part I. A standardized apparatus (Telos ®, Germany) was used to apply medial stress to the axially unloaded ankle in order to produce talar tilt in steps of 5kp up to 25kp. 3-D Coordinates were calculated from a 4 video camera setup, and an anterior – posterior x-ray was made in 6 stress positions. After this the ligamentum fibulo-talare anterior (LFTA) was sectioned and the measurement procedure repeated. In the final step the ligamentum fibulo calcaneare was additionally cut. Talar tilt angle was measured from x-rays and the rotation angle by means of the helical axis.
(III) In vivo: the marker system was fixed to the tibia using adhesive double-sided tape and with a special shoe construction to fix it to the calcaneus. 3D calculation of marker coordinates in finite positions were performed from a synchronized four-camera video setup using the Peak Performance® system.
Twelve subjects were tested in sitting position without foot-ground contact. They moved their feet from a neutral position into dorsiflexion and (while maintaining dorsiflexion) in eversion and inversion. This was done to minimize movements of the ankle joint (in dorsiflexion) during the measurement procedure. Each camera was equipped with an optical trigger system in order to mark the exact video frame for 3-D calculations.

RESULTS:
Figure 1: X-ray - talar tilt (solid line) and helical axis rotation angle (dotted line) from one specimen under stress from 0 to 25 kp applied medially to the ankle.



(I) The in vitro investigation revealed a mean deviation from repeated measurements of 10.6 degrees (± 4.6) and an inclination of 45.7 (± 5.6).
(II) With 20kp stress the average talar tilt was 6° for the intact joint, 11° with LFTA cut and 18° with both ligaments cut.
The correlation of x-ray talar tilt with the helical axis method was $r^2 = 0.86$ for the intact joint, 0.96 with LFTA cut, and 0.99 with both ligaments cut.
(III) From 12 subjects a mean deviation of 23 (± 13) and an inclination of 46 (± 10) were calculated. The correlation of deviation and inclination was r = 0.8.

DISCUSSION: This study was designed to apply a method for determining ankle joint and subtalar joint axes in vivo using the helical axis procedure. The early work of Manter (11), Root (16) and Inman (6) was performed on cadaveric specimens. Other authors performed in vivo radiographs (10, 12), modeling (8, 17) or clinical examination (15).
For one ankle specimen the average results were 10.6° deviation and 45.7° inclination obtained from repeated measurements. Averages (12 intact left ankles) of 23° deviation and 46° inclination were found in vivo. These values are comparable to results of other authors (6, 11, 17, 18).
However, the parameters are highly susceptible to measurement errors and noise (14, 19). Especially the calculation of orientation of the axis in three-dimensional space depends on the accuracy of the marker coordinates. The rotation angle is less susceptible to measurement errors. For this reason we used this parameter to determine the relation of standard stress x-ray talar tilt and rotation of the talus relative to the tibia after cutting the lateral ankle ligaments. The increased talar tilt and the strong correlation (r^2 0.9) support the assumption that ankle ligaments act as guiding bundles. The helical angle of rotation with a medial stress of 15kp increased by 100% after the LFTA was cut and by 300% after the LFC was cut (values compared to those with the joint capsule intact).
Nigg et al. (13) investigated the relationship of height of the longitudinal arch of the foot and the incidence of ankle injuries. No significant correlation could be found, but the authors discussed an increased influence of subtalar eversion with respect to chronic knee injuries. The oblique orientation of the subtalar joint axis is discussed with respect to tibial torque and distribution of load on the ball of the foot (8). McClay (12) speculated that with less inclination of the STA with respect to the horizontal plane, together with a large amount of eversion, the greater would be the chance for the foot to be injured. On the other hand, a STA that is more inclined, together with a large amount of tibial rotation, would tend to injure the knee.
Phillips et al. (15) investigated the relation between STA and special anatomical points of the foot in order to calculate the torque of the subtalar joint under axial load. Because of the form of the trochlea tali one can conclude that in full dorsiflexion of the ankle joint the eversion-inversion movement provides a possible approach to the real STA. But the amount of experimental effort makes the method applicable for laboratory use only.

CONCLUSION: Based on the correlation of the angles and on the relation of this axis to other ankle joint stabilizing structures (muscles, tendons) it is concluded that this subtalar joint complex may play an important role in the incidence of sudden inversion injuries. Thus, determination of the axis in vivo could serve as a powerful tool for prediction of ankle joints with a high risk for ankle sprains.

REFERENCES:

Barnett, Ch., Napier, J. R. (1952). The Axis of Rotation at the Ankle Joint in Man. 1st Influence upon the the Form of the Talus and the Mobility of the Fibula. *J. Anat. Lond.* **86**, 1-8.

Bishop, K. E. (1969). Rodrigues' Formula and the Screw Matrix. *Journal of Engineering for Industry*, 179-185.

Blankevoort, L. R., Huiskes, De Lange, A. (1990). Helical Axes of Passive Knee Joint Motions. *J. Biomech*. **23**(12), 1219-1229.

Hart, R. A., Mote, C.D. Jr., Skinner, H. B. (1991). A Finite Helical Axis as a Landmark for Kinematic Reference of the Knee. *J. Biomech. Eng.* **113**(2), 215-22.

Hicks, J. H. (1953). The Mechanics of the Foot I. The Joints. *J. Anat. Lond.* **87**, 345-357.

Inman, V. T. (1976). The Joints of the Ankle. Baltimore: The Williams and Wilkins Company.

Jacob, H. A. C. (1989). Biomechanics of the Forefoot (pp. 1-109). Dissertation. Strathclyde: University of Strathclyde, Bioengineering Unit.

Jones, R. L. (1945). The Functional Significance of the Declination of the Axis of the Subtalar Joint. *Anat. Rec.* **93**, 151-159.

Kinzel, G. L., Hall Jr, A. S., Hillberry, B. M. (1972). Measurement of the Total Motion between two Body Segments. I. Analytical Development. *J. Biomech.* **5**(1), 93-105.

Lundberg, A., Svensson, O. K., Bylund, C., Goldie, I., Selvik, G. (1989). Kinematics of the Ankle/Foot Complex-Part 2: Pronation and Supination. *Foot Ankle Int.* **9**(4), 248-253.

Manter, J. T. (1941). Movements of the Subtalar and Transverse Talar Joints. *Anat. Rec.* **80**(4), 397-409.

McClay, I., Bray, J. (1996). The Subtalar Angle: A Proposed Measure of Rearfoot Structure. *Foot Ankle Int.* **17**(8), 499-502.

Nigg, B. M., Cole, G. K., Nachbauer, W. (1993). Effects of Arch Height of the Foot on Angular Motion of the Lower Extremities in Running. *J. Biomech.* **26**(8), 909-916.

Panjabi, M. M. (1979). Centre and Angles of Rotation of Body Joints, a Study of Errors and Optimization. *J. Biomech.* **12**(12), 911-920.

Phillips, R. D., Lidtke, R. H. (1966). Clinical Determination of the Linear Equation for the Subtalar Joint Axis. *J. Am. Podiatr. Med. Assoc.* **82**(1), 1-20.

Root, M. L., Weed, J. H., Sgorlato, T. E. (1966). Axis of Motion of the Subtalar Joint, an Anatomical Study. *J. Am. Podiatr. Med. Assoc.* **56**, 149-155.

van den Bogert, A. J., Smith, G. D., Nigg, B. M. (1994). In Vivo Determination of the Anatomical Axes of the Ankle Joint Complex: An Optimization Approach. *J. Biomech.* **27**(12), 1477-1488.

van Langelaan, E. J. (1983). A Kinematical Analysis of the Tarsal Joints. An X-Ray Photogrammetric Study. *Act. Orthop. Scand.* **54**(204), 1-265.

Woltring, H. J., Huiskes, R., De Lange, A., Veldpaus, F. E. (1985). Finite Centroid and Helical Axis Estimation from Noisy Landmark Measurements in the Study of Human Joint Kinematics. *J. Biomech.* **18**(5), 379-389.