

An experimental setup for the measurement of forces on a human cadaveric foot during inversion

Citation for published version (APA):

Ottevanger, E. J. C., Spoor, C. W., Leeuwen, van, J. L., Sauren, A. A. H. J., Janssen, J. D., & Huson, A. (1989). An experimental setup for the measurement of forces on a human cadaveric foot during inversion. *Journal of Biomechanics*, 22(8-9), 957-962. [https://doi.org/10.1016/0021-9290\(89\)90080-8](https://doi.org/10.1016/0021-9290(89)90080-8)

DOI:

[10.1016/0021-9290\(89\)90080-8](https://doi.org/10.1016/0021-9290(89)90080-8)

Document status and date:

Published: 01/01/1989

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

TECHNICAL NOTE

AN EXPERIMENTAL SETUP FOR THE MEASUREMENT OF FORCES ON A HUMAN CADAVERIC FOOT DURING INVERSION

E. J. C. OTTEVANGER*, C. W. SPOOR*, J. L. VAN LEEUWEN*, A. A. H. J. SAUREN†,
J. D. JANSSEN† and A. HUSON*

*Research Group on Human-Joint Biomechanics, Department of Anatomy, University of Leiden,
Postbus 9602, 2300 RC Leiden, The Netherlands; †Faculty of Mechanical Engineering, Eindhoven
University of Technology, Eindhoven, The Netherlands

Abstract—An experimental setup was developed for statically measuring seven vertical and three horizontal reaction forces on the foot. In the setup, the leg can be simultaneously loaded (1) by a vertical force, (2) by an externally applied axial moment, and (3) by simulated muscle forces. The foot is free to invert under influence of the external loads. Statical analysis and test experiments were used for evaluation. The setup can be used in combination with Roentgen photogrammetry to measure bone positions simultaneously with forces.

INTRODUCTION

In the Department of Anatomy in Leiden, a long-term program of investigations on the kinematical behaviour of the human foot is in progress (Ambagtsheer, 1978; van Langelaan, 1983; Spoor, 1984; Benink, 1985; Fievez *et al.*, 1986). It was shown that during inversion, induced by exorotation of the tibia, the movements of the bones in the human tarsus can be described with the use of moving rotation axes. The successive positions of these axes follow fixed patterns and are approximated by a bundle of discrete helical axes (van Langelaan, 1983). Preserved foot-leg specimens were used for Roentgen photogrammetric analysis. The results are also relevant for the *in vivo* situation (Benink, 1985).

Progress in this research program requires an advanced setup for simultaneous measurements of external loads on, and displacements of, a foot-leg specimen during exorotation of the tibia.

The ultimate goal is to develop a model to investigate the mechanical function of the ligaments and the articular facets in a loaded human foot during inversion.

EXPERIMENTAL SETUP

An experimental setup was developed, in which ten reaction forces on the foot in seven different points of an axially loaded foot-leg specimen (Figs 1 and 2) can be measured. Forces are measured with the foot in the neutral position, and during inversion. Inversion of the foot is achieved by exorotation of the tibia, induced by an adjustable moment about a vertical axis, or by simulating muscle forces by pulling muscle tendons. The moment and simulated muscle forces as well as the angle of rotation of the tibia are simultaneously measured.

The *in vivo* situation to be simulated is a vertically loaded and exorotated lower leg standing on a horizontal plane. The foot is supported at seven places. Vertical forces under the heel and the metatarsals balance the vertical load, whereas friction forces at these same places compensate the exorotating moment. Reaction forces on the foot are simplified by concentrating:

- (1) the metatarsals friction force into one point fixed to the fifth metatarsal head;
- (2) the heel friction force into one point fixed to the calcaneus and
- (3) the vertical reaction forces into points fixed to the five metatarsals and to the calcaneus.

The setup (Figs 1 and 2) has the following important features:

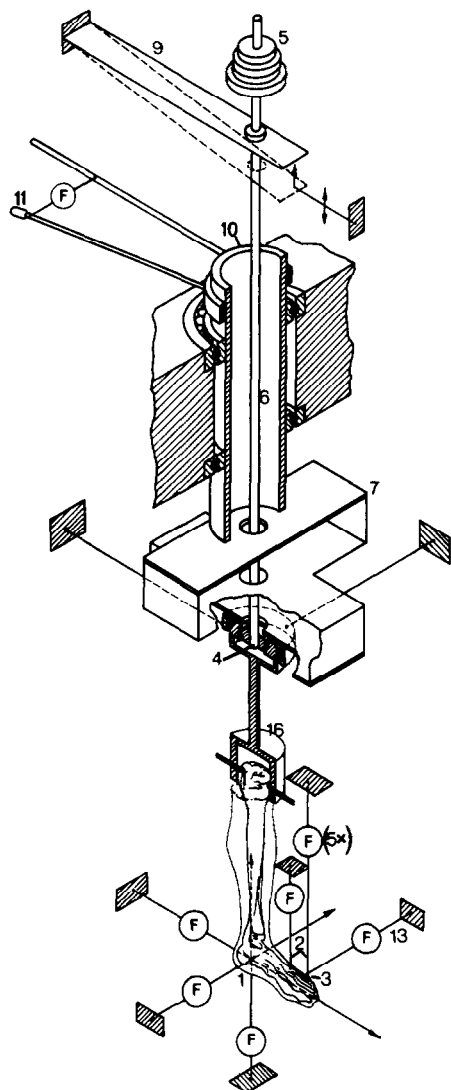
- (1) instead of allowing the heel to slip or to roll, we chose an exactly defined rotation centre for the heel. To this purpose, a screw with a spherical head was driven into the plantar side of the tuber calcanei. The sphere rests in a cup fixed to the framework of the setup (Figs 1 and 2:1).
- (2) Six other places to support the foot were chosen: the five metatarsal heads and the base of the fifth metatarsal bone (Figs 1 and 2:2). In these places, the foot is supported by small cylinders which are suspended from steel wires (drilled through the bone).
- (3) Another screw with a spherical head was driven into the lateral side of the fifth metatarsal head. The sphere was placed in a socket which could not move in a medio-lateral direction. This induces inversion as an effect of exorotation of the tibia (Figs 1 and 2:3).

The proximal fixation of the tibia presents specific problems:

- (1) inversion generally raises the longitudinal foot arches, thus lifting the tibia;
- (2) an inversion tilt of the calcaneus causes a lateral shift of the distal tibia and fibula.

These problems were solved using two horizontal orthogonal flexible rods which allow one point, named A (Figs 1 and 2:4), fixed to the proximal tibia, to move in a vertical direction only. The two rods also allow a limited tilt about any horizontal axis to compensate for the lateral shift of the ankle during inversion. The kinematical constraints to point A guarantee a uniquely determined position of the lower leg. At point A a moment about a vertical axis, and a vertical force (Figs 1 and 2:5) are applied by a special coupling and by a long vertical steel rod (Figs 1 and 2:6), respectively.

Benink found that vertical loads over 340 N damage some embalmed preparations during inversion, and that an increase of the vertical load from 160 to 340 N had no effect on the patterns of tarsal movement. We chose 300 N as a safe upper limit.



Figs 1 and 2. F, Force transducers (Fig. 1 only); 1, rotation centre for the heel (sphere in cup); 2, six wires supporting the forefoot; 3, sphere fixed to lateral side of the fifth metatarsal; 4, point A, just below the coupling and above the fixation ring; 5, axial load; 6, vertical steel rod transmitting the axial load; 7, 'Koster' coupling (see text); 8, orthogonal steel rods fixed to transducers (Fig. 2 only); 9, leaf spring; 10, hollow tube transmitting the moment; 11, moment handle; 12, Roentgen cassettes (Fig. 2 only); 13, long balanced arm; 14, weight and pulley (Fig. 2 only); 15, force transducer and swivel (Fig. 2 only); 16, fixation ring for tibia.

Asang (1984) reported damage in some fresh post mortem lower extremities for moments over 40 Nm. Our setup was designed to measure moments up to 40 Nm, which allows a comparison with results of Benink (1985), who applied maximally 25 Nm.

The special coupling ('Koster' coupling, Figs 1 and 2:7) was designed to transmit a moment about a vertical axis without prohibiting the small tibial tilt and the vertical translation of point A. This coupling has a high torsional stiffness in a horizontal plane and a much lower stiffness for all other moments, or forces in any direction.

An orthogonal co-ordinate system (X, Y, Z) is rigidly attached to the framework. Its origin is situated in the centre of the cup in which the sphere under the calcaneus is placed. The

Z -axis is parallel to the vertical load (and to the rotation axis of the setup), and its positive direction is opposite to gravity. The Z - Y plane approximately coincides with the sagittal plane of the tibia, its positive Y -axis pointing towards the toes. The positive X -axis points laterally in a right foot. The force acting on the heel is resolved in X, Y and Z components by three orthogonal rods fixed to uniaxial force transducers (Fig 2:8). Also, the other force transducers are aligned parallel to the co-ordinate axes. Forces acting on the metatarsals are transmitted to force transducers by 75 cm long suspending wires. Horizontal deviations of the vertical loading axle are prevented by a leaf spring (Figs 1 and 2:9). Around this axle, a hollow tube (Figs 1 and 2:10) transmits the moments applied through the moment handle (Figs 1 and 2:11). For Roentgen photogrammetry, we use two vertical and approximately orthogonal films (Fig. 2:12). A Roentgen tube faces each of the films. The foot points horizontally towards the films under angles of about 45° .

During inversion, the sphere attached to the fifth metatarsal head moves downward (maximally 10mm). In order to avoid bending moments applied to the force transducer, a long balanced horizontal arm (Figs 1 and 2:13) was used. The aluminium arm passes under a Roentgen cassette to a suspension point. The arm is suspended from a leaf spring. Counter weights bring the centre of gravity of the arm very close to the suspension point. The point to which the force is transmitted is about 1000 mm away from the sphere at the fifth metatarsal, and lies at the same level as the sphere, just above the suspension point of the arm. Here, the arm is connected to a flexible rod (100 mm) fixed to a force transducer. This way, the direction error of the medio-lateral force on the fifth metatarsal is limited to 0.6° .

To simulate muscle forces, tendons were loaded isotonically or isometrically. An isotonic muscle force (60 N) can be simulated by means of a weight (15 N) hanging over a pulley (Fig. 2:14). The weight over the pulley increases the vertical load on the tibia and causes a horizontal moment on the leg. This moment causes a horizontal force on the foot and a positive or negative contribution to the external moment. The magnitudes of these will be discussed later. Isometric forces are simulated using force transducers (Fig. 2:15) connected via a swivel to a tendon.

PREPARATION OF THE SPECIMENS

The foot-leg specimens were taken from cadavers preserved *in toto* (van Langelaan, 1983; Benink, 1985). A radiograph was made of each specimen to exclude joint pathology. Holes for support wires were drilled through the metatarsal heads and through the base of the fifth metatarsal. Two metal spheres (Figs 1 and 2:1 and 3) were attached. Bone cement was applied to the lateral side of the head of the fifth metatarsal, giving the screw the necessary support. Next, force transducers were set to zero, the specimen was mounted, and an axial load was applied. According to Benink (1985), we waited 10 min for the specimen to adapt itself to the vertical loading.

RESULTS FOR VALIDATION OF THE SETUP

The directions of the force transducers under the heel deviate less than 0.2° from the corresponding co-ordinate axis directions, being virtually constant owing to the small deformation of the force transducers (less than 0.1 mm). The maximum direction error of the medio-lateral forces on the forefoot is 0.2° for the neutral position. For maximum inversion, this error can increase to 0.6° (see above). The error in balance of the long arm causes a vertical force of less than 0.03 N. For the vertical forces on the metatarsal heads, the error is less than 0.8° in the neutral position, changing less than 0.2° during inversion. The flexible rods to point A (Figs 1 and 2:4) can be directed parallel to the two horizontal

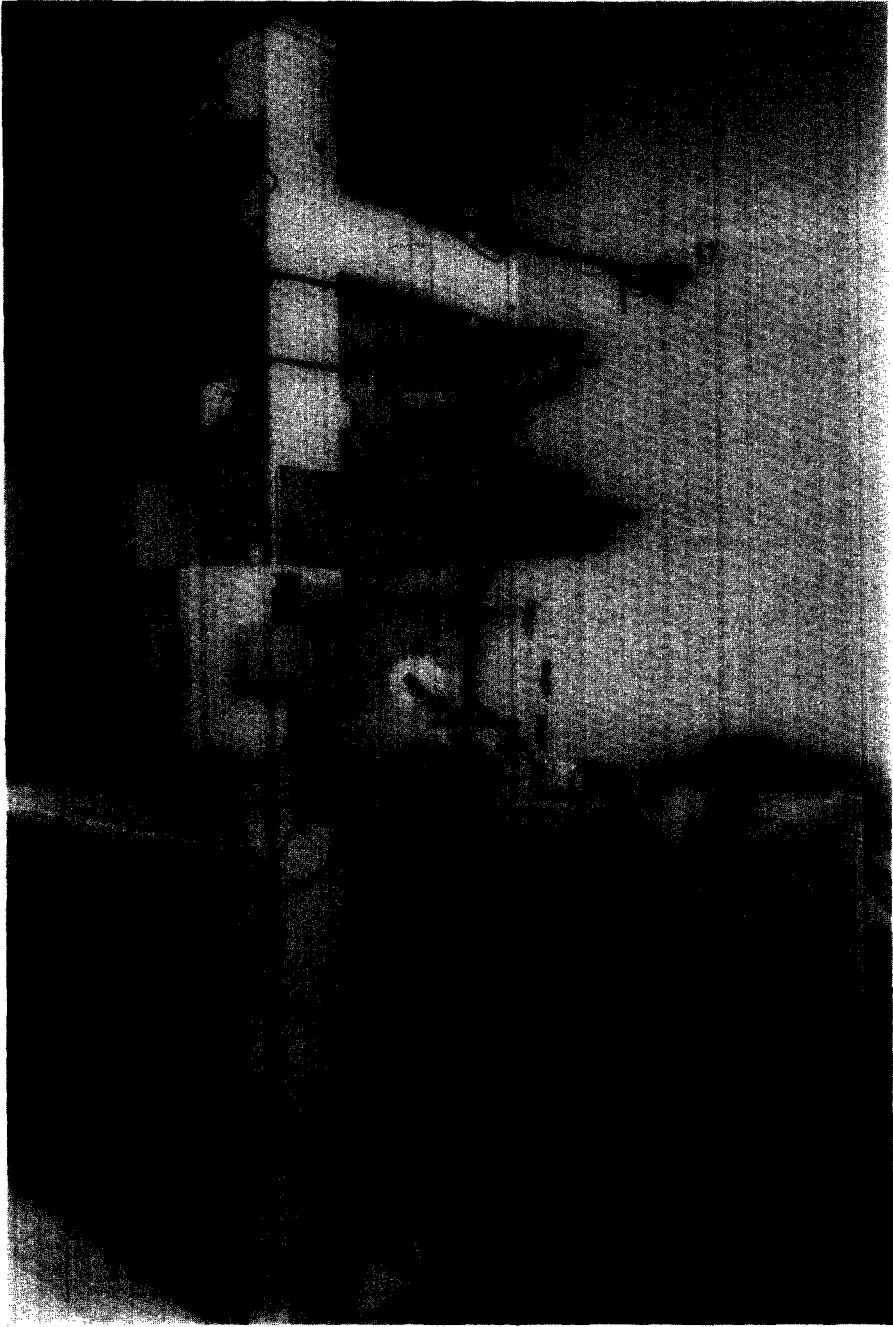
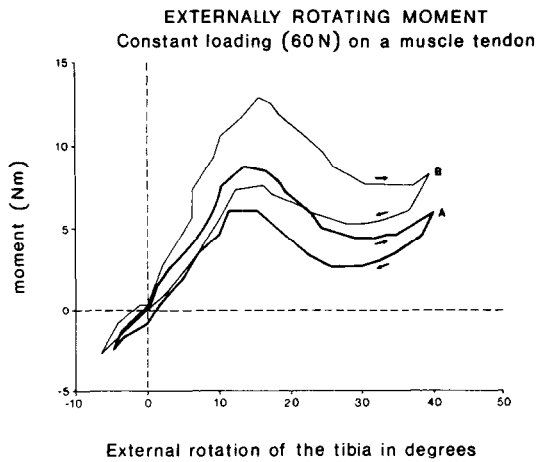


Fig. 2.



Figs 3, 4 and 5. Externally rotating moment on a lower-leg specimen as a function of the exorotation angle, with (B) and without (A) a constant load of 60N on the peroneus longus (Fig. 3), the tibialis posterior (Fig. 4), and the tibialis anterior (Fig. 5) tendons.

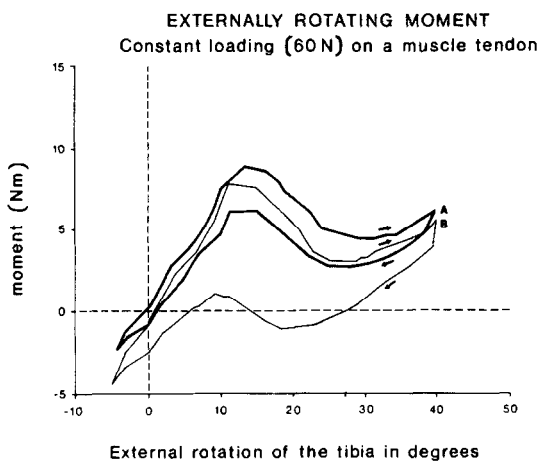


Fig. 4.

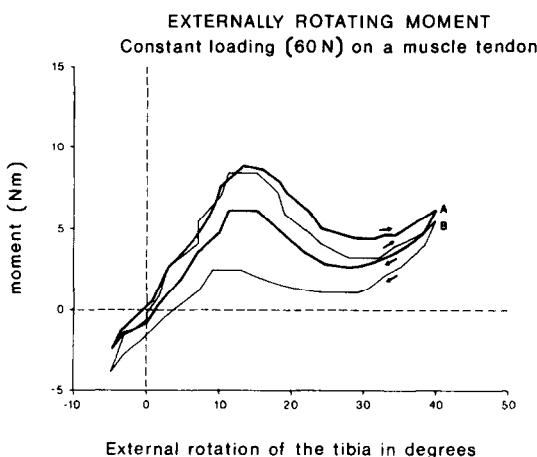


Fig. 5.

co-ordinate axes within 0.2° . The tibial rise during inversion will rarely exceed 15 mm (Benink, 1985). A 15 mm rise bends the horizontal rods and the elastic coupling, resulting in an additional vertical load of 18 N. A horizontal force on one of the slanting rods (estimated at less than 8 N) causes a vertical force component of less than 1 N. The tilt of the fixation ring engenders a counteracting moment in the 'Koster' coupling and the horizontal rods near point A. This moment is balanced by two opposite horizontal forces: one at point A and one at the plantar level of the foot. The tilt is found to be 3° or less. The stiffness of the 'Koster' coupling and the horizontal rods is 50 Nm rad^{-1} . The counteracting moment in the coupling and the horizontal force on the foot are less than 1.35 Nm and 1.8 N respectively. The rod transmitting the axial load (Figs 1 and 2:6) deviates not more than 0.2° from the vertical direction. With an axial load of 300 N, this results in a horizontal force of less than 1.2 N at point A. The forces and moment induced by the pulley weights follow from simple equilibrium equations. An added weight of 15 N increases the vertical load by 15 N, changes the external moment by less than 0.059 Nm, and adds a horizontal force of less than 2.3 N to the heel.

ASSESSMENT OF MUSCLE FUNCTION: AN APPLICATION OF THE SETUP

We simulated an isotonic muscle force of 60 N, in separate experiments, for the m.tibialis anterior, m.tibialis posterior and m.peroneus longus. We measured the exorotating moment as a function of the tibial rotation angle (Figs 3, 4 and 5). Figure 3 shows that loading of the m.peroneus longus requires a higher input moment, so this muscle acts as an antagonist during inversion of the tarsus. In Figs 4 and 5, loading of each of the tibialis muscles appears to reduce the needed moment. The difference between the two tibialis muscles is greatest from maximal inversion back to the neutral position. In this movement, the m.tibialis posterior proved to be a more effective inverter than the m.tibialis anterior.

DISCUSSION AND CONCLUSIONS

A new experimental setup is demonstrated. This setup can be used to simultaneously measure forces on the foot, and positions of bones in the foot and in the leg. Also, the functional effects of the lower-leg muscles can be tested, in a well defined situation. Measured data can be used as input for a quasi-statical model to simulate inversion of the foot.

Acknowledgements—The authors gratefully acknowledge the technical assistance of Professor Dr Ir M. P. Koster, Eindhoven University of Technology, Mr A. P. van Kempen and Mr G. J. Verschragen, Physiology Department of Leiden, and Ir A. J. Blom, Instrumentmakerschool, Kamerlingh Onnes Laboratorium, Leiden.

The authors are grateful to Dr Ph. Evans of the Accident Unit of Norfolk and Norwich Hospital, Norwich, for checking the manuscript. This study was supported by the Foundation for Fundamental Biological Research (BION), which is subsidized by the Netherlands Organization for the Advancement of Pure Research (ZWO).

REFERENCES

Ambagtsheer, J. B. T. (1978) The function of the muscles of the lower leg in relation to movements of the tarsus. Thesis, Leiden.
 Asang, E. (1974) Biomechanics of the human leg in alpine

- skiing. *Biomechanics IV* (Edited by Nelson, R. C. and Morehouse C. A.), pp. 236-242. University Park Press, Baltimore, MD.
- Benink, R. J. (1985) The constraint mechanism of the human tarsus. *Acta orthop. scand.* **56**, (Suppl.) 215.
- Fievez, A. W. F. M., Huson, A. and Spoor, C. W. (1986) A kinematical analysis of the ankle joint in relation to lateral ligamentous and capsular injuries. *Acta morph. neerl-scand.* **24**, 60.
- Langelaan, E. J. van (1983) A kinematical analysis of the tarsal joints. *Acta orthop. scand.* **54**, (Suppl) 204.
- Spoor, C. W. (1984) Explanation, verification and application of helical-axis error propagation formulas. *Hum. Mvmt. Sci.* **3**, 95-117.