CHAPTER X

CALCULATIONS OF ABSOLUTE TIBIAL AND TARSAL HELICAL MOVEMENTS

10.1 ABSOLUTE TIBIAL MOVEMENTS

10.1.1 Directions and positions of tibial axes, partial range

The absolute tibial helical axes describe the movements of the tibia in relation to the origin 0 and the coordinates of the cage.
To begin with, the findings regarding preparation nr. 1. In the dorsoplantar projection (Figure 10-1a), the direction of the axes is from anterolateral to posteromedial.
In the frontal projection (Figure 10-1b), this direction is from laterosuperior to medioinferior.
In the sagittal projection (Figure 10-1c), it is clearly visible that the tibial bundle is projected outside the tibial pylon, just posteriorly to the posterior edge of the tibial projection. The very steep axes have a direction from anterosuperior to posteroinferior.

Combining these directions of three projected bundles, we find for the absolute tibial movements not one single axis, but a *bundle, just posteriorly to the tibial pylon passing through the tuber calcanei with a direction from anterolatero-superior to posteromedioinferior.*
If the helical movement is positive (clockwise) viewed in the anteroposterior direction, the axial directions show that exorotation occurs, with a minimal and therefore negligible eversion component. The distance travelled by the tibia will be maximal close to and obliquely in front of the malleolus lateralis (fibulae) and minimal at the level of the posterior portion of the malleolus medialis (tibiae).

1. The deviation angle π, TI 10°, without phase 1, in all 10 preparations (Table 10-1).
Taking the L-R difference into account, π varied from - 102.6° to 89.6°. The mean value of π in the 10 preparations varied from -33.7° to 78.8°. However, because the axes are very steep, these large differences affect the position only little. Change of quadrants occurred in 5 of the 10 preparations.

Table 10-1. Deviation angles of tibial (π TI 10°) with summation, mean and range of deviation angles.

Specimen		R	R	R	R	R	R	R	L	L	L
		1	2	3	4	5	6	7	8	9	10
Phase											
π	1	-79.6 (280.4)	17.9	-51.6 (308.4)	-136.7 (223.3)	-147.7 (212.3)	-72.5 (287.5)	49.5	6.1	-97.3 (262.7)	37.3
π	2	-42.0 (318.0)	-20.7 (339.3)	-38.5 (321.5)	-19.1 (340.9)	-102.6 (257.4)	-37.4 (322.6)	43.0	5.4	-89.6 (270.4)	62.0
π	3	-37.3 (322.7)	-9.0 (351.0)	-38.0 (322.0)	-9.9 (350.1)	-39.7 (320.3)	39.9 (320.1)	33.6	4.8	-76.8 (283.2)	22.9
π	4	-38.0 (322.1)	26.5	-20.8 (339.2)	-0.2 (359.8)	-40.3 (319.7)	-29.5 (330.5)	52.4	3.9	-70.3 (289.7)	16.8
π	5	-31.8 (328.2)	26.8	-10.5 (349.5)	13.5	-38.0 (322.0)	-22.6 (337.4)	54.4	-3.0 (357.0)	-74.3 (285.7)	-11.5 (348.5)
π	6	-19.3 (340.7)	37.3	-3.2 (356.8)	30.3	-18.9 (341.1)				-82.9 (277.1)	-36.4 (323.6)
$\Sigma\ \pi$		-168.4	60.9	-111.0	14.6	-239.5	-129.4	183.4	14.1	-393.9	53.8
$\overline{\pi}$		-33.7	12.2	-22.2	-2.9	-47.9	-32.6	45.9	3.5	-78.8	10.8
R π		22.8	58.0	35.3	49.4	83.7	17.3	41.4	8.4	19.3	98.4

Table 10-2. Inclination angles of tibial axes (φ TI 10°) with summation, mean and range of inclination angles.

Specimen		R	R	R	R	R	R	R	L	L	L
		1	2	3	4	5	6	7	8	9	10
Phase											
φ	1	87.8	88.1	89.3	89.3	85.2	88.5	87.7	87.0	88.0	87.4
φ	2	86.8	86.3	86.1	84.5	85.6	85.5	87.2	84.9	88.2	87.9
φ	3	86.9	87.1	85.9	82.0	84.3	83.7	86.8	82.2	88.0	84.8
φ	4	85.6	87.1	85.0	84.2	84.3	84.1	86.4	81.8	87.5	84.4
φ	5	85.1	87.0	85.1	85.3	86.5	85.3	87.0	82.8	87.3	88.5
φ	6	86.5	88.0	85.5	86.3	86.1				87.2	88.3
$\Sigma\ \varphi$		430.0	435.5	427.6	422.3	426.8	338.6	347.4	331.7	438.2	433.9
$\overline{\varphi}$		86.2	87.1	85.5	84.5	85.4	84.7	86.9	82.9	87.6	86.8
R φ		1.8	2.3	1.1	4.3	2.2	1.8	0.8	3.1	1.0	4.1

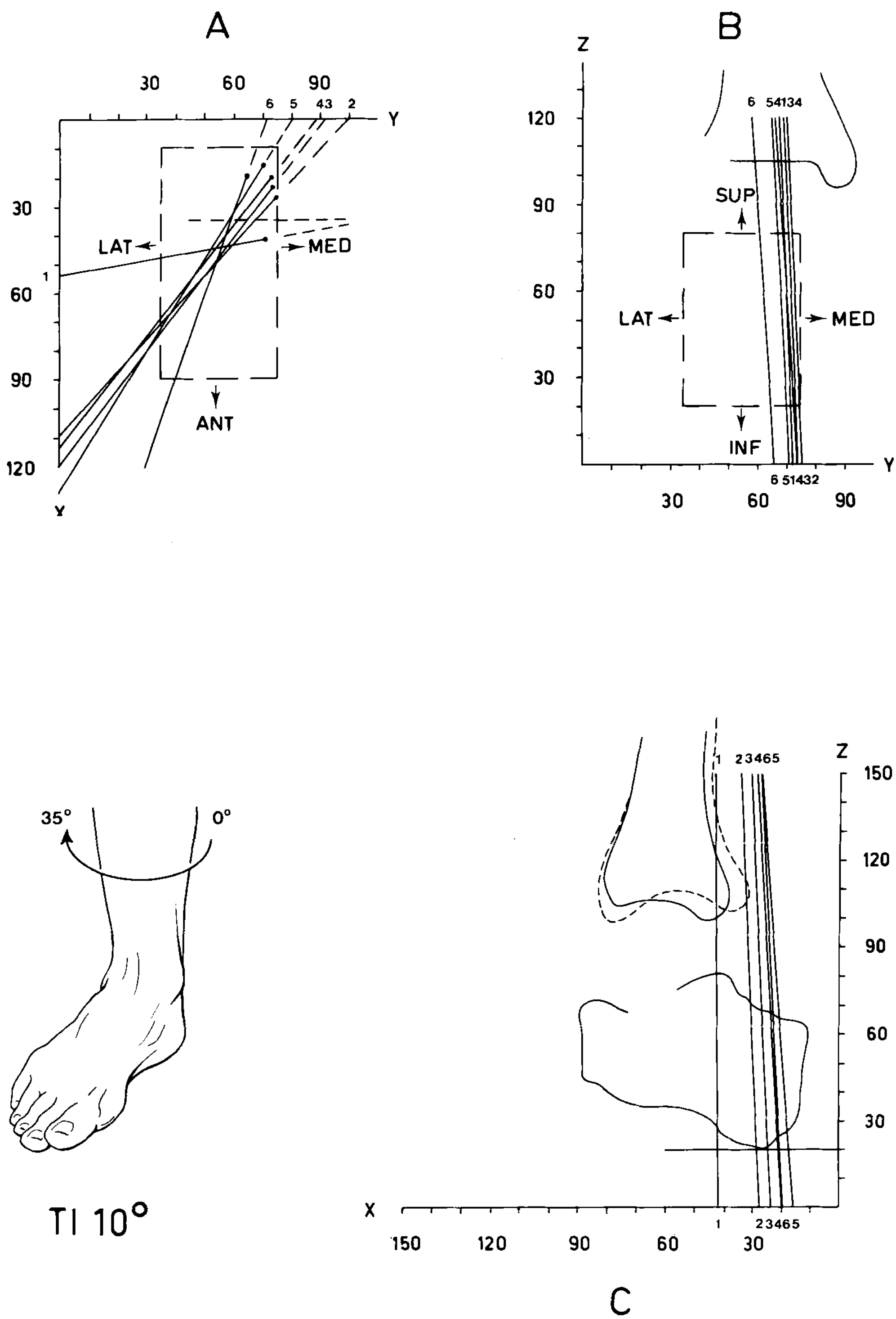

Figure 10-1. Projections of absolute tibial helical axes. Partial range TI 10°.

2. The inclination angles, φ TI 10°, without phase 1 in all 10 preparations (Table 10-2).
In nearly all phases, the direction of the axes was from anterosuperior to postero-inferior; accordingly, the axes always made an anteriorly open angle.
While φ varied from 81° to 94.4°, its mean value for the bundle varied from 82.9° to 87.6°. Accordingly, the TI 10° axes always make a very wide, almost 90° angle with the basal plane.

If we combine the determinations of π and φ, we find that for all 10 preparations this gives us a very steep bundle of axes, with a direction from anterosuperior to posteroinferior and pointing slightly either in the lateral or in the medial direction.

3. The angles R π and R φ of the bundle width, the bundle angle (Table 10-1, 10-2).
The variation angle R π varied greatly, from 8.4° to 98.4°. For Rφ, on the other hand, narrow angles were found, from 0.8° to 10.1°.

4. Movement of the axis along a path of points of intersection.
All the absolute tibial helical axes we have found have a point of intersection with the XY plane of the cage. This lies 20 mm below the top of the calcaneal support. In vivo, between the calcaneal support and the basal plane there will be a layer of subcutaneous fatty tissue and skin (height approx 10 mm).
Considering the very steep axes, the points of intersection with the XY-plane of the cage that we have determined provide a reasonable approximation of the pattern of points of intersection at the level of the top of the calcaneal support. Table 10-3 lists the XY-coordinates of the points of intersection of every axis with the XY-plane of the cage (step size 10°) for the 10 preparations. In Figure 10-2, the points of intersection have been drawn in and connected with each other (per preparation). The result is a sort of *path*. All these paths describe an arc from anteromedial to posterolateral. Therefore, in the drawings we shall encounter the right-left difference: anticlockwise for the seven right-sided, and clockwise for the three left-sided preparations.
It is also noticeable that there are preparations with large ranges of movement, such as nrs 4 and 5, with variations in the X-direction of 40 mm and 50 mm, respectively, while other preparations show only small differences in extreme values of movement in the X-direction, such as nrs 7 and 9, with 11.5 mm and 1.5 mm, respectively.

N.B.: It is interesting to note that there are similar patterns of the points of intersection with the XY-plane in preparations with different deviation directions. Regardless of whether the direction of the axis is anteromediosuperior or anteriolaterosuperior, we constantly find a path of points of intersection from anteromedial to posterolateral.
For purposes of comparison, let us consider the points of intersection of the

Table 10-3. Centres of intersection tibial axes (TI 10°) with XY-plane (z = o).

	Phase	X	Y		Phase	X	Y
	2	27.52	74.61		2	35.80	78.46
	3	23.70	73.63		3	20.56	84.30
1R	4	19.81	73.54	6R	4	16.16	78.25
	5	16.22	70.61		5	21.50	69.05
	6	19.32	64.80				
	Phase	X	Y		Phase	X	Y
	2	23.51	53.02		2	27.59	47.37
	3	16.23	51.08		3	25.78	46.06
2R	4	-11.03	41.99	7R	4	31.66	41.52
	5	0.20	39.24		5	39.18	39.04
	6	15.61	39.84				
	Phase	X	Y		Phase	X	Y
	2	37.94	67.61		2	19.13	42.76
	3	23.18	73.66		3	- 2.12	42.14
3R	4	13.41	70.72	8L	4	- 5.13	46.36
	5	15.31	62.13		5	4.26	55.42
	6	19.70	54.53				
	Phase	X	Y		Phase	X	Y
	2	5.68	68.76		2	31.49	51.47
	3	- 21.43	65.58		3	29.57	53.07
4R	4	- 15.57	54.51	9L	4	29.33	56.46
	5	1.91	43.42		5	30.03	59.96
	6	19.07	34.57		6	30.02	61.77
	Phase	X	Y		Phase	X	Y
	2	42.10	77.43		2	24.42	32.69
	3	18.51	82.32		3	13.91	34.52
5R	4	2.74	83.82	10L	4	10.06	39.40
	5	- 7.44	77.49		5	16.34	48.94
	6	- 7.65	68.93		6	19.32	56.19

'ideally vertical' helical axis (axes) of the HMTA which are the reflection of a fixed vertical, mechanical axis; computation method and examination method (stepwise) are analogous. For the upper as well as for the lower combination of marking balls of the HMTA, the points of intersection of their helical axes with the XY-plane were computed. As Table 10-4 shows, the points of intersection for both combinations fell within an area of only *approx 1 sq.mm. Moreover there was no question of one single pattern of the points of intersection!*

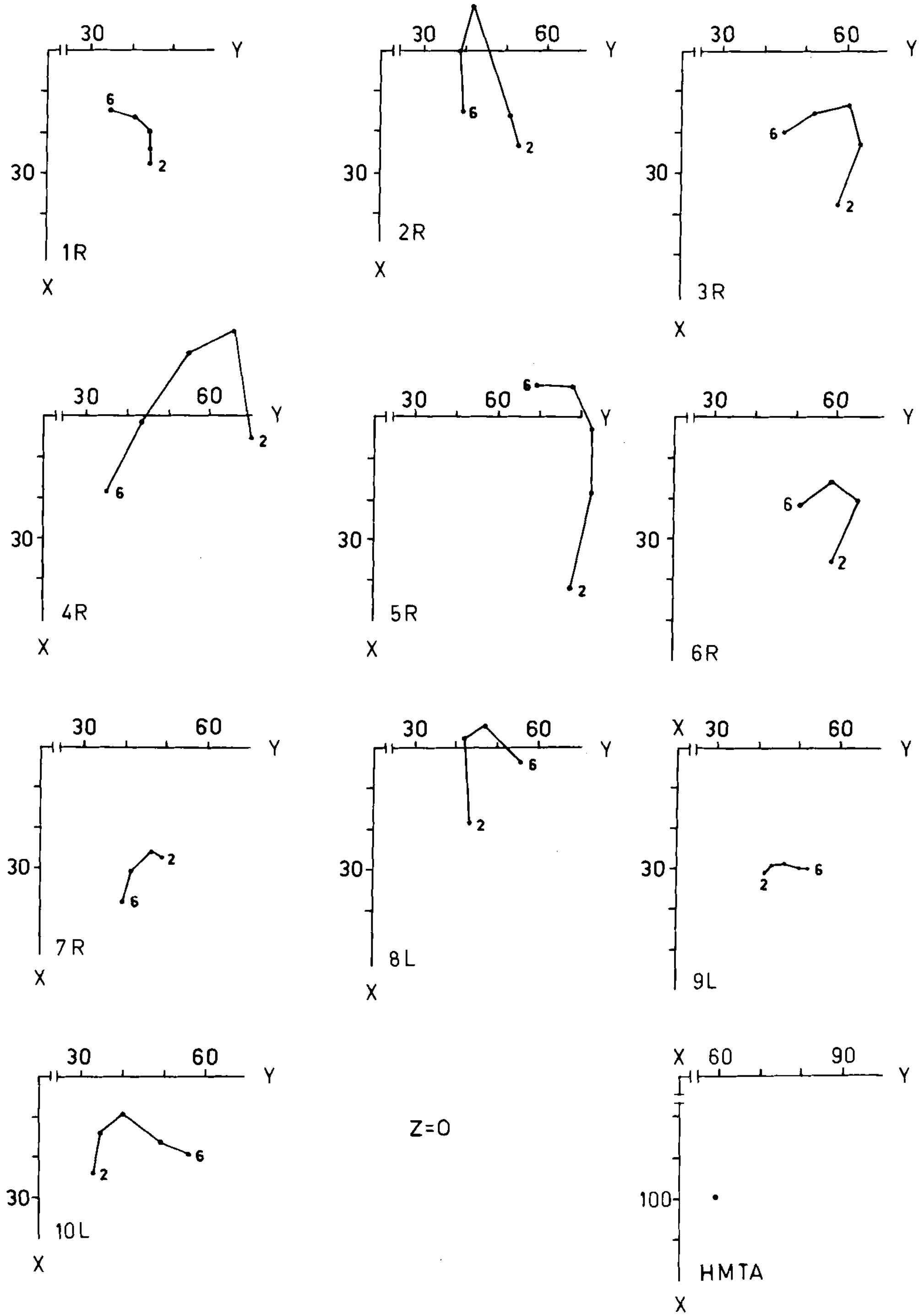

Figure 10-2. Paths of the centres of intersection of the absolute tibial helical axes with XY-plane. Right below: concentration of centres of intersection HMTA helical axes with XY-plane.

Table 10-4. Centres of intersection HMTA helical axes with XY plane. (z = o)

Upper combination HMTA			Lower combination HMTA		
Phase	X	Y	Phase	X	Y
1	100.10	59.30	1	100.01	59.75
2	99.84	59.04	2	99.66	59.02
3	99.44	59.35	3	99.50	58.78
4	98.79	59.76	4	99.94	59.22
5	99.37	58.70	5	99.96	59.36
6	100.20	58.44	6	99.97	59.44

5. Comparison with the literature.
The literature practically unanimously mentions one single rotation axis for the tibial rotation; allegedly, direction and position are the same irrespective of the phase of the movement. The illustrations then show an axis of symmetry of the tibia, passing through the talocrural joint, corpus tali and calcaneus.
In a recent study by J. Rastegar and N. Miller, the preliminary results are reported of a kinematic analysis of the tibial rotations in one foot-lower leg preparation (1979). The authors report a 13 mm displacement of the point of intersection of the rotation axis with the basal plane for the transition from 6° endorotation to 23° axorotation. These authors, also, conclude that there can be no question of a constant or near constant axis of rotation for internal-external rotation of the human ankle joint.

10.1.2 Rotations and translations along tibial axes, partial range

1. Rotations, α TI 10°, without phase 1 (Table 10-5)
The absolute tibial rotation varies from 8.5° to 10.5°. Although in our discussions we always refer to a step size of 10°, the computations show that actually the tibial rotation per phase has not been a constant 10° but varied in magnitude. These 'deviations' from the tibial laterorotation step of 10° were caused by a number of factors. While performing the experiments, we each time rotated the central rotation axis of the cage through an angle of 5°, according to the graduation of the step mechanism. The universal joint and the locking ring transmitted this rotation to the tibia. After each step, the central rotation axis was secured by means of the clamping screw. The 'deviations' may have been due to calibration errors and play in the step mechanism; slipping of the central rotation axis in the clamping screw; play and imperfect alignment in the universal joint, play between the tibia and the locking ring. The effect of the above-named factors cannot be calculated exactly, but has probably been slight.

Table 10-5. Tibial rotations (TI α 10°) and translations (TI t 10°), partial range.

Specimen		R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10	
	Phase											
t	1	0.4	0.1	0.1	0.3	0.0	0.2	-0.6	0.3	0.0	0.5	TI mm
α		8.4	9.5	9.3	8.7	9.3	8.9	9.3	8.9	9.8	9.9	TI°
t	2	1.0	0.4	0.9	1.6	1.6	1.3	-0.5	1.0	0.1	0.5	TI mm
α		8.5	9.8	9.3	9.2	8.8	9.5	10.2	9.4	9.8	10.1	TI°
t	3	0.7	-0.1	1.5	1.3	3.2	1.6	-0.3	0.9	0.1	0.4	TI mm
α		8.6	10.4	10.1	10.5	8.6	10.3	9.9	10.3	9.8	10.4	TI°
t	4	0.7	-0.7	1.3	-0.1	4.0	1.1	-0.4	0.3	0.1	0.1	TI mm
α		9.3	10.3	10.4	10.5	9.5	10.5	9.5	10.3	9.9	10.4	TI°
t	5	0.7	-0.5	0.7	-0.7	3.2	0.5	-0.5	-0.3	0.1	-0.2	TI mm
α		10.0	9.8	10.2	9.8	10.5	10.2	9.4	8.5	9.6	9.8	TI°
t	6	0.2	-0.3	0.4	-0.7	1.6				0.2	-0.3	TI mm
α		9.4	9.8	10.0	8.5	10.5				9.4	9.9	TI°

Experiments showed that tibial torsion is an important causative factor. The tibial torsion depends on the moment applied and on the amount of load on the tibia. Benink (1978) has measured the magnitude of the moment. He found that with increasing exorotation of the tibia first an increasing and subsequently a decreasing rotation moment had to be applied.
The absolute tibial rotations have been computed on the basis of the changes of position of the tibial marking balls situated in the distal part of the tibia (medial malleolus).
During the first phase or first few phases, when the foot offers no 'resistance', the tibial moment will be relatively small. When the tibial moment is maximal, tibial torsion will also be maximal. When torsion is maximal, the exorotation of the tibia at the proximal end will approach closely to the exorotation of the tibia distally (at the site of the marking balls). The distortion of the tibia then remains approximately constant. While performing the experiments, now, we found that certain preparations showed a maximum of the moment sooner, i.e. after only a few phases, than others. Evidently, it depends on the preparation: indiviual variability of foot-lower leg preparations. Another interesting finding was that virtually all preparations showed a decrease of the moment in the last phase of the experiment.
Although, therefore, in this study we always refer to a step size of tibial laterorotation of 10° as measured with the step mechanism, *actually the computed absolute tibial laterorotations mostly were slightly less than 10°, and a few times slightly more than 10°.*

As the axial directions show, the direction of rotation in all phases corresponded to a latero(exo)rotation.

2. Translations, t Tl t 10°, without phase 1 (Table 10-5)
These varied from -0.7 mm to 1.6 mm.
The direction of the translation was constantly positive in certain preparations (nrs 1, 3, 5, 6 and 9), first positive and then negative in four others (nrs 2, 4, 8 and 10) and always negative in one (nr 7). In other words, in 9 out of 10 preparations, the tibia moves upward, which may or may not be followed by a downward movement; in one preparation (nr 7), the tibia 'descends' constantly during exo (latero)rotation.

It should be noted that this does not mean that the upward movement along the helical axes equals the upward movement that can be measured along the central rotation axis of the testing apparatus. The two axes, namely, do not coincide. Unfortunately, we have not recorded this vertical change of position of the central axis, as Benink has done later. Consequently, the data from the study of Ambagtsheer and Benink cannot be compared in any simple manner with our data.
We have given some extra attention to the three preparations with negative translations. Might the downward movement be linked to a particular calcaneal tilt? In Table 10-6 we list the direction of translation of the tibia and the direction of deviation of the calcaneal axes for preparations 2, 4 and 7 in the various phases.

Table 10-6. Comparison tibial translation with deviation tibial and calcaneal axes. (specimen no. 2, 4, 7)

	Specimen no. 2 R	Specimen no. 4 R	Specimen no. 7 R
Tibial translation	+ - - - -	++ - - -	- - - -
Deviation calcaneal axes	+++++	- ++++	++++
	anteromedial ⟶	posterolateral	

The table shows that negative translations are observed particularly in the presence of positive directions of deviation for the calcaneal axes. In other words: the tibia descends during exorotation if the absolute calcaneal helical axis runs from anteromedioinferior to posterolaterosuperior. The converse applies as well: positive translations are observed virtually always when the direction of the absolute calcaneal axes is from anterolateroinferior to posteromediosuperior (see Table 10-7).

Table 10-7. Comparison tibial translation with deviation calcaneal axes. (specimen no. 1, 3, 5, 6, 8, 9, 10)

	Specimen no. 1 R	Specimen no. 3 R	Specimen no. 5 R	Specimen no. 6 R
Tibial translation	+++++	+++++	+++++	++++
Deviation calcaneal axes	- - - - -	- - - - -	- - - - -	- - - -
	anterolateral → posteromedial			

	Specimen no. 8 L	Specimen no. 9 L	Specimen no. 10 L
Tibial translation	+++ -	+++++	+++ - -
Deviation calcaneal axes	++++	+++++	+++++
	anterolateral → posteromedial		

The above has the following functional anatomical consequences. If there is a calcaneal helical axis with a direction from anteromedial to posterolateral, there is a flexion component for the calcaneus in addition to the inversion, resulting in tilt of the calcaneus, while the talus with the tibia descends toward the basal plane. This contrasts with a calcaneal helical axis with a direction from anterolateral to posteromedial where in addition to the inversion, an extension component occurs. This causes the calcaneus to tilt and also to rise, so that tibia and talus move in the proximal direction.

10.1.3 Directions and positions of tibial axes, total range

Figure 10-9 shows among other things the three projections of the single absolute tibial helical axis as it was computed for preparation nr. 1 for the total range of movement.

From the combination of projections we may conclude that the tibia appears to rotate around a steep axis that is situated outside the distal tibial pilon, viz posteriomedially to it, with a direction from anterolaterosuperior to postero-medioinferior. This axial position matches a typical exorotation movement of the tibia.

1. The deviation angles, π TI 30°/35° in all 10 preparations (Table 10-8)

Taking into account the left-right difference, this angle varied from -55.8° to 72.4°. The mean deviation angle was -1.8°; variation range: 139.1°. (irrespective of the sign $\bar{\pi}$: 30.9)

N.B.: Therefore, we did not find a similar direction of the deviation axis in all ten preparations. In five of them (nrs. 1, 3, 5, 6 and 10), the direction of the axis was

Table 10-8. Tibial deviation angles (π TI 30°/35°) and inclination angles (φ TI 30°/35°) total range.

Specimen	TI π 30°/35°	TI φ 30°/35°
1 R	- 36.9° (323.1°)	87.0°
2 R	14.5°	87.5°
3 R	- 16.7° (343.3°)	86.7°
4 R	3.8°	86.3°
5 R	- 55.8° (304.2°)	87.3°
6 R	- 34.1° (325.9°)	86.0°
7 R	54.7°	87.4°
8 L	0.0°	84.0°
9 L	- 72.4° (287.6°)	87.6°
10 L	19.9°	87.4°

from anterolaterosuperior to posteromedioinferior; in four preparations, on the other hand (nrs 4, 7 and 9), it was from anteromediosuperior to posterolatero-inferior. In preparation nr 8, the direction of deviation paralleled the X-axis. No relationship with the left-right difference was found to exist. On the other hand, the direction of the tibial rotation axis does depend in part on the arrangement of the preparation in the cage; also, in the experimental set-up, the tibia in rotating had 3° freedom of movement (see also Chapter 4.3).

2. The inclination angles, φ TI 30°/35° for all ten preparations (Table 10-8)
This angle varied from 84.0° to 87.6°. The mean inclination angle was 86.7°; range of variation 3.6°.
The direction of the axis was similar in all preparations, from anterosuperior to posteroinferior.

10.1.4 Rotations and translations along tibial axes, total range

1. The rotations, α TI 30°/35° (Table 10-9)
The rotations α varied from 27.7° to 35.1°. The mean tibial rotation was 32.1°; range of variation 7.4°.
As was to be expected, the direction of rotation in all ten preparations was that corresponding to an exorotation.

2. The translations, t TI 30°/35° (Table 10-9)
The translations t varied from -1.3 mm to 6.9 mm. The mean translation amounted to 1.4 mm.
The direction of translation was *not* the same for all ten preparations; in eight of them (nrs 1, 3, 4, 5, 6, 8, 9 and 10) it was positive, i.e. the tibia moved upward, away from the origin; in two preparations (nrs 2 and 7), the direction of the translation was negative. This matches the partial range data.

Table 10-9. Tibial rotations (α TI 30°/35°) and translations (t TI 30°/35°) total range.

Specimen	TI α 30°/35°	TI t 30°/35°
1 R	31.4°	+ 1.9 mm
2 R	34.8°	- 0.7 mm
3 R	34.5°	+ 2.4 mm
4 R	32.7°	+ 0.5 mm
5 R	33.4°	+ 6.9 mm
6 R	29.4°	+ 2.3 mm
7 R	28.6°	- 1.3 mm
8 L	27.7°	+ 0.9 mm
9 L	33.8°	+ 0.4 mm
10 L	35.1°	+ 0.6 mm

3. Comparison with the literature

Only in Ambagtsheer's thesis (1978) we do find data on translation of the tibia for the shift from the starting position to incomplete supination (comparable to our end position). An upward shift of the tibia as the result of supination was measured in four of the five preparations studied, viz 0, 1, 2, 3 and 4 mm; mean 2 mm. Variation 0 to 4 mm for a rotation averaging 27°.

N.B.: The maximal supination position mentioned by Ambagtsheer is a position in which the forefoot is allowed to turn the sole medially. Ambagtsheer's 'incomplete supination' corresponds to an exorotation of the tibia during which the entire forefoot still remains in contact with the floor, so that it *is* comparable to our total range data. In our discussion of the other absolute tarsal movements, also, we shall each time compare our computations in this manner with Ambagtsheer's data.

Here again, the fact, already discussed on page 93, should be kept in mind that these tibial movements are not simply comparable to the translations along the tibial rotation axes which we have computed.

10.2 ABSOLUTE TALAR MOVEMENTS

10.2.1 Directions and positions of talar axes, partial range

The absolute talar helical axes describe the movements of the talus in relation to the system of axes in the cage.

First the results of preparation nr 1.

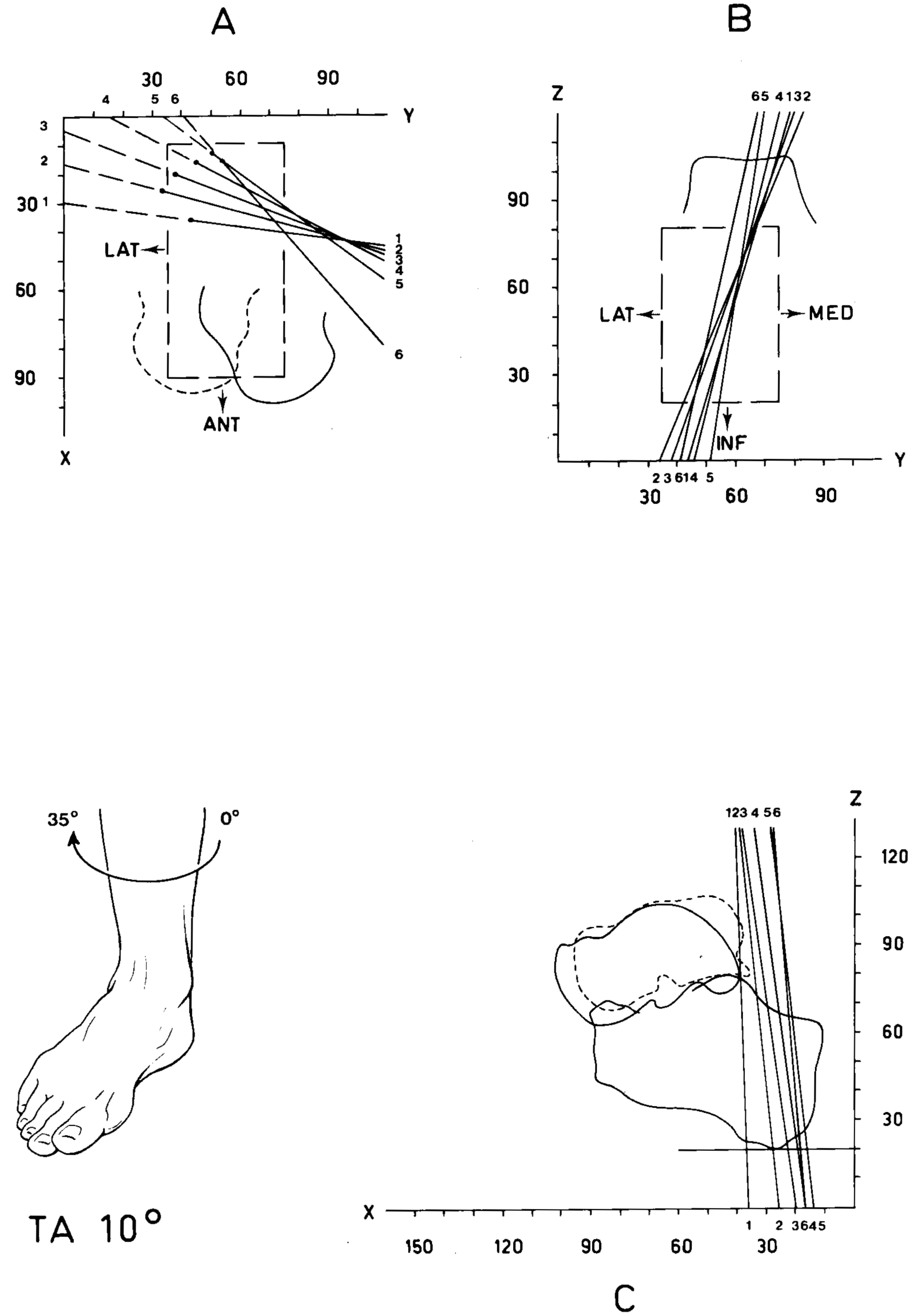

Figure 10-3. Projections of absolute talar helical axes. Partial range TI 10°.

In the dorsoplantar projection, Figure 10-3a the direction of the axes is from anteromedial to posterolateral.
In the frontal projection, Figure 10-3b the direction of the axes is from mediosuperior to lateroinferior.
Figure 10-3c shows the sagittal projection. A noticeable aspect is that the bundle of axes here is projected outside the talus, viz. posteromedially to it. The direction of the fairly steep axes is from anterosuperior to posteroinferior.

The combination of the three projections shows that the talus moves round helical axes that run posteromedially to the talus, passing through the tuber calcanei, with a direction from anteromediosuperior to posterolateroinferior.
In case of a positive pitch, considering the axial directions, there occurs a combined abduction-eversion movement of the talus, with a slight extension component. The abduction component is the major component of the movement.
The range of movement will be maximal at the head of the talus and minimal at the posterior talar process.

1. The deviation angles, π TA 10°, without phase 1, for all 10 preparations (Table 10-10)

This table shows that the deviation angles varied greatly; taking into account the left-right difference, π varied from -129.6° to 178.9°. The mean value for each of the preparations varied from -9.5° to 94.9°. Accordingly, the absolute talar helical axis (nearly) always made a wide angle with the 'longitudinal axis' of the foot. In 8 of the 10 preparations (nrs 1, 2, 3, 4, 5, 6, 7 and 10), a decrease of the deviation angle π was observed; the axis moved toward the sagittal plane, which might be followed by its 'passing through' this plane in the lateral direction.

2. The inclination angles, φ TA 10°, without phase 1 in all 10 preparations (Table 10-11)

In most phases in the 10 preparations we found a direction of the axes from anterosuperior to posteroinferior.
In most phases, the absolute talar axis made an anteriorly open angle. The inclination angle varied from 24.9° to 95.8°. The mean value for each preparation varied from a minimum of 60.3° to a maximum of 87.5°; in other words, the talar axes always made a wide angle with the basal plane.
In the changes of φ in relation to the basal plane a trend was observed: in all preparations, there was an increase of φ with sometimes a decrease in those phases that followed a change of quadrant. In other words: the talar helical axis straightened up and then in 6 of the 10 preparations (nrs 2, 4, 7, 8, 9, 10) during the last phase and/or the last phase but one 'passed through the 90°'; the axis, as it were, lent over backwards and consequently made a dorsally open angle.
Combining the data on deviation and inclination of the axes we find that in the 10 preparations in most phases the direction of the axis is from *anteromedio-superior to posterolateroinferior.*

Table 10-10. Deviation angles of talar axes (π TA 10°) with summation, mean and range of deviation-angles.

Specimen	R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10
Phase										
1	82.1	70.4	103.5	88.4	82.5	84.4	58.0	299.2	300.6	287.7
2	74.6	70.7	83.5	70.7	79.8	77.5	58.3	-56.8 (302.2)	-62.9 (297.1)	-63.1 (296.9)
3	68.1	67.8	72.7	61.1	86.8	71.2	43.7	-54.6 (305.4)	-59.8 (300.2)	-53.9 (306.1)
4	61.7	68.3	67.2	41.3	80.3	63.3	-77.0 283.0	-120.5 239.5	-60.6 299.4	-24.8 335.2
5	53.4	63.7	61.5	-91.0 (269.0)	69.4	54.9	178.9	-147.2 (212.8)	-89.2 (270.8)	67.5
6	40.8	-104.5 (255.5)	54.4	-129.6 (230.4)	66.0				-61.4 (241.4)	115.2
$\Sigma\pi$	298.6	166.0	339.3	-47.5	382.3	266.9	203.9	379.7	-333.9	40.9
$\overline{\pi}$	59.7	33.4	67.9	-9.5	76.5	66.7	51.0	-94.9	-66.8	8.2
R π	33.8	175.2	29.1	200.3	20.8	22.6	239.6	92.6	29.4	178.3

Table 10-11. Inclination angles of talar axes (φ TA 10°) with summation, mean and range of deviation angles.

Specimen	R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10
Phase										
φ 1	73.3	65.8	83.6	76.1	66.6	77.6	81.2	78.0	80.4	73.7
φ 2	66.8	67.8	70.4	66.3	59.6	65.3	83.3	69.0	82.2	72.9
φ 3	69.1	73.4	64.0	68.2	59.5	61.5	86.7	86.6	84.6	78.7
φ 4	74.0	80.4	65.0	79.6	61.7	66.3	89.1	60.7	86.2	87.7
φ 5	79.0	87.1	71.8	83.5	65.2	75.5	(90.9)	24.9	86.6	87.3
φ 6	83.4	84.0	79.3	73.5	74.0		89.1		86.5	95.8 (84.2)
$\Sigma\varphi$	372.3	392.7	350.5	371.1	320.0	268.6	350.0	241.2	339.5	422.4
$\overline{\varphi}$	74.5	78.5	70.1	74.2	64.0	67.2	87.5	60.3	67.9	84.5
R φ	16.6	28.2	15.3	17.2	14.5	14.0	9.1	61.7	4.4	17.1

However, in 6 of the 10 preparations (nrs. 2, 4, 7, 8, 9 and 10), a change of quadrant occurred during the last phase or the last phase but one. Thus, we find a direction of the axis from anteromedioinferior to posterolaterosuperior in preparation 2, phase 6, preparation 4, phase 5 and preparation 10, phase 6. A direction of the axis from anterolateroinferior to posteromediosuperior was seen in preparation 4, phase 6; preparation 7, phase 5 and preparation 8, phases 4 and 5, and a direction from anterolaterosuperior to posteromedioinferior was seen in preparation 7, phase 4 and preparation 10, phase 5.

3. The angles R π and R φ of the bundle width (Tables 10-10 and 10-11)
The angle Rπ ranged from 22.6° to 239.6°. The angle Rφ ranged from 9.1° to 40.2° in 9 of the 10 preparations.
In one preparation (nr 8) a particularly large variation angle was found, viz 61.7°, because in this preparation in the last phase an extremely low value for φ was found.

4. Movement of the axis along a path of points of intersection
We have computed the points of intersection of the absolute talar and the absolute tibial axes with the basal plane. For the 10 preparations, the X- and Y-coordinates of these points of intersection are listed in Table 10-12. In Figure 10-4 they have been interconnected to form a path. Because the *absolute talar helical axis* moves in the lateral direction and also upward, *a pattern (path) of displacement from lateral to medial* is to be expected in the XY-plane. Such paths were indeed found for the 10 preparations. In Figure 10-4 we have also once more indicated the paths for the absolute tibial axes. The paths were found never to coincide, the talar path mostly was situated laterally to the tibial path. There was a constant pattern of combinations of the displacements in the paths. For the seven right-sided preparations we always saw a clockwise pattern of displacement in the absolute talar path combined with a counterclockwise pattern of displacement in the absolute tibial path. The inverse applied to the three left-sided preparations.

5. Comparison with the literature
The literature known to us contains no list of talar helical rotation axes during stepwise tibial rotation. Frequently, on the other hand, we have encountered in the literature the opinion that the talus is carried along 'passively' in the tibio-fibular socket during tibial laterorotation, so that talar abduction and tibial latero-rotation would take place round one and the same rotation axis. This is not correct: as described above, the absolute talar movements and the absolute tibial movements take place round different rotation axes in two different bundles!

Table 10-12. Centres of intersection talar axes (TA 10°) with XY-plane (Z=O).

	Phase	X	Y		Phase	X	Y
	2	26.0	34.1		2	34.5	38.7
	3	20.3	37.9		3	24.6	32.7
1R	4	16.7	45.3	6R	4	18.9	38.1
	5	13.8	51.5		5	20.0	47.9
	6	16.9	56.0				

	Phase	X	Y		Phase	X	Y
	2	19.4	19.0		2	20.3	42.6
	3	16.6	25.3		3	21.9	46.3
2R	4	20.3	32.1	7R	4	26.3	48.0
	5	25.0	37.2		5	32.2	45.0
	6	29.0	43.4				

	Phase	X	Y		Phase	X	Y
	2	34.2	36.9		2	10.2	76.5
	3	22.9	28.6		3	- 5.3	78.3
3R	4	16.5	27.8	8L	4	13.3	77.0
	5	16.4	34.0		5	85.8	82.3
	6	19.8	40.3				

	Phase	X	Y		Phase	X	Y
	2	5.1	26.0		2	22.9	57.7
	3	- 13.9	26.0		3	24.8	56.7
4R	4	- 14.7	42.4	9L	4	26.4	57.8
	5	8.0	56.5		5	28.6	61.0
	6	34.1	56.6		6	30.2	62.3

	Phase	X	Y		Phase	X	Y
	2	18.9	30.6		2	15.8	60.7
	3	16.6	31.7		3	12.9	53.6
5R	4	10.4	32.3	10L	4	15.5	44.4
	5	- 2.5	33.6		5	18.2	44.7
	6	- 5.6	42.5		6	23.7	46.3

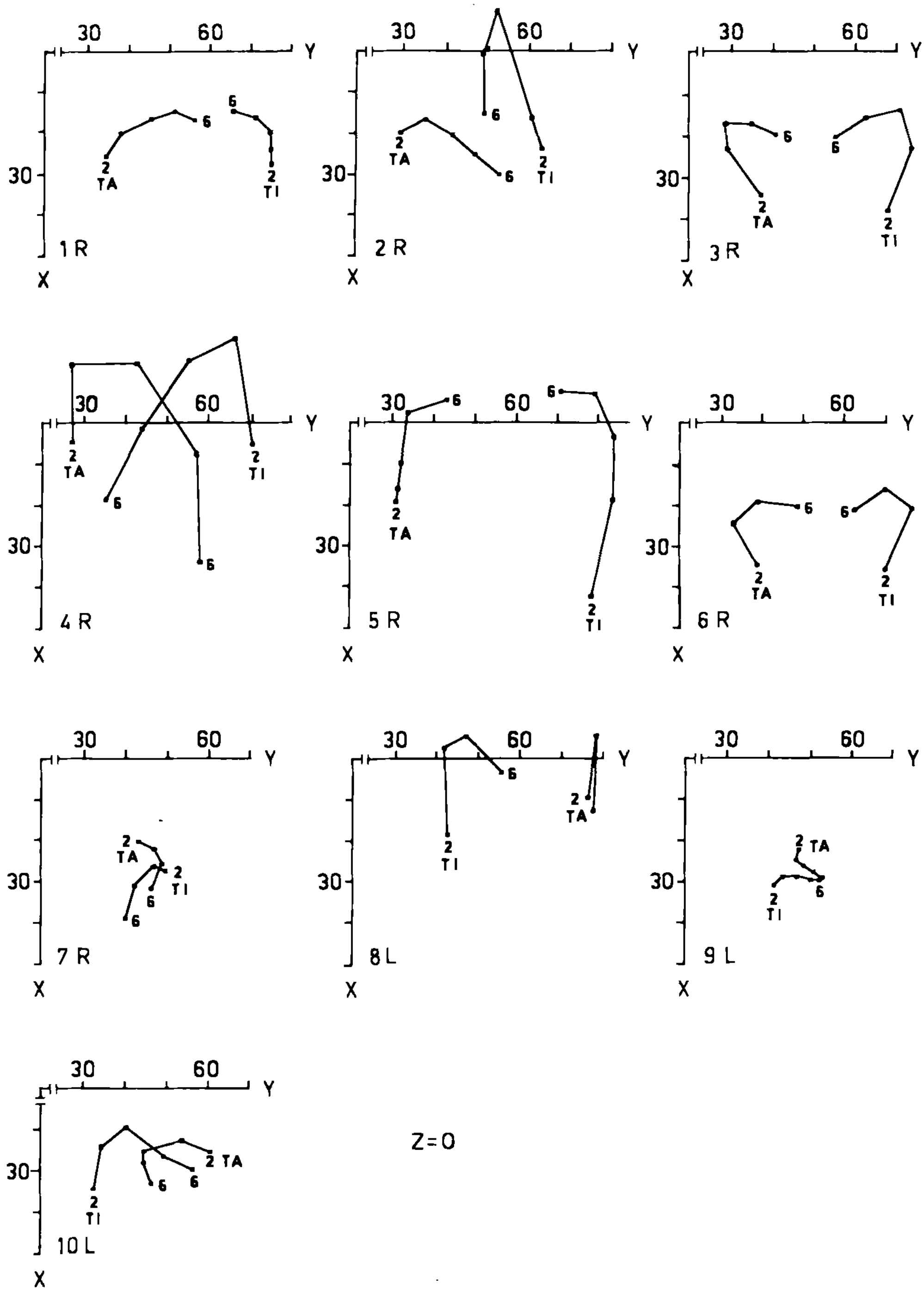

Figure 10-4. Paths of the centres of intersection absolute tibial and talar helical axes with XY-plane (Z=O).

10.2.2 Rotations and translations along talar axes, partial range

1. Rotations, α TA 10° without phase 1 (Table 10-13)
The absolute talar rotation varied from 14.2° with a tibial rotation of 10.3°, to 6° with a tibial rotation of 9.4°.
A talotibial rotation surplus was observed in 27 of the 47 phases. Such a rotation surplus may occur because during each step there is rotation round two rotation axes (that of the tibia and that of the talus) which differ in position and direction.
In all preparations we saw a gradual increase of the rotation, with a decrease in the last phase. The direction of rotation was clockwise for the 7 right-sided and counterclockwise for the 3 left-sided preparations (viewed in the a-p direction).
In other words, in most phases there was a combined abduction-eversion movement with a small extension component; since the axis turns steeper, the abduction component of the talus increases with increasing tibial laterorotation.
In the 6 preparations with change of quadrant in the last few phases (see Chapter 10.2.2), the position of the axes shows that in these phases there occurs a combination of abduction, eversion and flexion.

Table 10-13. Talar rotations (TA α 10°) and translations (TA t 10°), partial range.

Specimen		R	R	R	R	R	R	R	L	L	L	
		1	2	3	4	5	6	7	8	9	10	
	Phase											
t	1	-0.6	-1.7	-0.1	-0.6	-0.6	-0.2	-0.8	-0.5	-0.4	-0.9	TA mm
α		7.1	7.1	2.7	4.7	2.7	4.3	5.7	6.1	6.7	8.5	TA°
t	2	-1.2	-2.5	-0.6	-2.3	-1.0	-0.8	-0.7	-1.6	-0.3	-1.3	TA mm
α		9.4	10.8	7.6	9.7	6.3	10.3	8.8	10.0	8.5	10.6	TA°
t	3	-1.3	-2.2	-2.0	-3.9	-1.1	-2.3	-0.4	-3.0	-0.1	-0.9	TA mm
α		9.6	11.0	12.4	12.2	8.3	14.2	8.6	11.3	9.2	10.7	TA°
t	4	-1.1	-1.6	-2.5	-1.7	-1.4	-2.3	-0.2	-5.0	0.1	-0.1	TA mm
α		10.1	11.0	13.7	11.2	11.9	14.1	7.1	8.4	9.2	10.3	TA°
t	5	-0.8	-0.6	-1.6	0.8	-2.4	-1.0	-0.5	-4.0	0.1	0.1	TA mm
α		10.4	10.3	12.3	9.4	13.7	11.6	6.0	7.6	8.7	10.1	TA°
t	6	-0.4	0.5	-0.7	1.0	-1.7				0.3	0.5	TA mm
α		9.4	8.9	10.8	7.3	11.8				8.4	9.5	TA°

The talotibial rotation surplus varied from 0.3° to 3.9°, mean 1.4°, range 3.6° (Table 10-14).
It was notible that there was no rotation surplus in two preparations (nrs 7 and 9).
In the other preparations, a rotation surplus was computed 27 times and a

Table 10-14. Talar rotations, (TA 10°) tibial rotations (TI 10°) and talotibial rotation differences (surplus +, deficit -) partial range.

Specimen		R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10
Phase											
	TA	7.1°	7.1°	2.7°	4.7°	2.7°	4.3°	5.7°	6.1°	6.7°	8.5°
1	TI	8.4°	9.5°	9.3°	8.7°	9.3°	8.9°	9.3°	8.9°	9.8°	9.9°
	diff.	-1.3°	-2.4°	-6.6°	-4.0°	-6.6°	-4.6°	-3.6°	-2.8°	-3.1°	-1.4°
	TA	9.4°	10.8°	7.6°	9.7°	6.3°	10.3°	8.8°	10.0°	8.5°	10.6°
2	TI	8.5°	9.8°	9.3°	9.2°	8.8°	9.5°	10.2°	9.4°	9.8°	10.1°
	diff.	+0.9°	+1.0°	-1.7°	+0.5°	-2.5°	+0.8°	-1.4°	+0.6°	-1.3°	+0.5°
	TA	9.6°	11.0°	12.4°	12.2°	8.3°	14.2°	8.6°	11.3°	9.2°	10.7°
3	TI	8.6°	10.4°	10.1°	10.5°	8.6°	10.3°	9.9°	10.3°	9.8°	10.4°
	diff.	+1.0°	+0.6°	+2.3°	+1.7°	-0.3°	+3.9°	-1.3°	+1.0°	-0.6°	+0.3°
	TA	10.1°	11.0°	13.7°	11.2°	11.9°	14.1°	7.1°	8.4°	9.2°	10.3°
4	TI	9.3°	10.3°	10.4°	10.5°	9.5°	10.5°	9.5°	10.3°	9.9°	10.4°
	diff.	+0.8°	+0.7°	+3.3°	+0.7°	+2.4°	+3.6°	-2.4°	-1.9°	-0.7°	-0.1°
	TA	10.4°	10.3°	12.3°	9.4°	13.7°	11.6°	6.0°	7.6°	8.7°	10.1°
5	TI	10.0°	9.8°	10.2°	9.8°	10.5°	10.2°	9.4°	8.5°	9.6°	9.8°
	diff.	+0.4°	+0.5°	+2.1°	-0.4°	+3.2°	+1.4°	-3.0°	-0.9°	-0.9°	+0.3°
	TA	9.4°	8.9°	10.8°	7.3°	11.8°				8.4°	9.5°
6	TI	9.4°	9.8°	10.0°	8.5°	10.5°				9.4°	9.9°
	diff.	0.0°	-0.9°	+0.8°	-1.2°	+1.3°				-1.0°	-0.4°

'rotation deficit' 19 times; only once were the rotations computed for talus and tibia identical.

We have not found earlier descriptions in the literature of this talotibial rotation surplus.

McCullough, C.J.M. and Burge, P.D. (1980), Johnson, E.C., Markolf, K.L. (1983), Fraser, G.A. and Ahmed, A.M. (1983) admittedly do describe differences in magnitude between talar and tibial rotation, but these differences were always due to the tibia leaving the talus behind, a 'rotation deficit'. These authors have carried out measurements in cadaver preparations at different loads with differently applied rotatory moments; cf. Table 10-15 in which the data from our investigation are also listed.

Table 10-15 lists the rotation surpluses and deficits both for the partial range data (PR) and for the total range data (TR).

Although our study dit not include a measurement of the rotatory moment which we applied for the tibia, we had some idea of it due to a study by Benink (1977)

Table 10-15. Talotibial rotation differences, axial loads and rotation torques.

	Talotibial rotation difference (degrees)	Load (N)	Rotation torque (Nm)
McCullough Burge (1980)	18° - 24° (deficit)	10 - 500 N	3 Nm
Johnson, Markolf (1983)	5° - 22° (deficit) mean 13.8° ± 4.6°	100 - 500 N	2 Nm
Fraser, Ahmed (1983)	± 20°	0 - 1000 N	0 - 20 Nm
Van Langelaan (1977)	0.1°-2.4° (deficit) PR 0.3°-3.9° (surplus) PR 0.3°-6.2° (deficit) TR 0.5°-1.7° (surplus) TR	160 N	1 - 20 Nm

who has measured these moments in a similar experimental set-up. They proved to vary from 1 Nm to 20 Nm.
Interestingly, this table shows that in our findings for the partial range, rotation surpluses as well as rotation deficits were computed, while for the total range, only a rotation deficit was found. Unlike ourselves, the above authors have not applied an accurate three-dimensional computation method, but confined themselves to skiagraphic studies. The limitations of this method have been described in Chapter 2.

2. The translations, t TA 10° without phase 1 (Table 10-13)
The absolute talar translation varied from -0.5 mm to 1.0 mm. This translation, also, showed a gradual increase followed by a decrease in the last phase. Large translations are not necessarily associated with large rotations. Considering the position of the axis, the direction of the translation was from anterosuperior to posteroinferior in the majority of the cases (39 out of 47); in other words, the talus moved toward the origin or the basal plane (or nearly always from medial or from lateral). (In preparations 7 and 8, as mentioned, a change of quadrants occurred four times; in these phases, the talus still moved toward the basal plane, but from the anterolateral direction).
In 8 of the 47 cases, the translation of the talus was away from the origin: 6 times with reversal of the axis in the last phase and/or the last phase but one, and twice in phases 4 and 5 in preparation nr. 9.

Comparing the translations of the talus and of the tibia, we note that the computation shows only negative translations for the talus whereas for the tibia, both positive and negative translations are found (see Table 10-16).
Therefore, in certain cases the talus and the tibia appear to move apart. As we have pointed out before, in the discussion of the absolute movements of the tibia, the vertical changes of position of the central axis of the experimental set-up do

Table 10-16. Tibial translations (TI 10°) and talar translations (TA 10°), partial range.

Specimen		R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10
Phase											
1	TA mm	-0.6	-1.7	-0.1	-0.6	-0.6	-0.2	-0.8	-0.5	-0.4	-0.9
	TI mm	0.4	0.1	0.1	0.3	0.0	0.2	-0.6	0.3	0.0	0.5
2	TA mm	-1.2	-2.5	-0.6	-2.3	-1.0	-0.8	-0.7	-1.6	-0.3	-1.3
	TI mm	1.0	0.4	0.9	1.6	1.6	1.3	-0.5	1.0	0.1	0.5
3	TA mm	-1.3	-2.2	-2.0	-3.9	-1.1	-2.3	-0.4	-3.0	-0.1	-0.9
	TI mm	0.7	-0.1	1.5	1.3	3.2	1.6	-0.3	0.9	0.1	0.4
4	TA mm	-1.1	-1.6	-2.5	-1.7	-1.4	-2.3	-0.2	-5.0	0.1	-0.1
	TI mm	0.7	-0.7	1.3	-0.1	4.0	1.1	-0.4	0.3	0.1	0.1
5	TA mm	-0.8	-0.6	-1.6	0.8	-2.4	-1.0	-0.5	-4.0	0.1	0.1
	TI mm	0.7	-0.5	0.7	-0.7	3.2	0.5	-0.5	-0.3	0.1	-0.2
6	TA mm	-0.4	0.5	-0.7	1.0	-1.7				0.3	0.5
	TI mm	0.2	-0.3	0.4	-0.7	1.6				0.2	-0.3

not equal the translations along the absolute tibial helical axis. Nor may these vertical changes of position be equated to the sum of all vertical components of the translations along the absolute calcaneal, talar and tibial helical axes.
When a body rotates round an axis outside it, and we follow the path of a point on this body, we find that if the axis is in an oblique position, the point may move up or down, depending on which side of the axis it is situated (see figure 10-5). The magnitude of this displacement depends on this distance between the point and the axis. In the vertical kinematic chain consisting of the calcaneus, talus and tibia, it is the point of contact between these bones that determine upward or downward direction of the movement. Moreover, in the course of the movement it is probably not always the same point that serves as point of contact. For this reason, no statements concerning the magnitude of these displacements can be made solely on the basis of the computed translations along the absolute axes.

3. Comparison with the literature

Here, again, a comparison with the literature is possible only in a few instances. MacConaill's study (1945), see Chapter 2, described, during abduction of the leg, an eversion of the talus for both steps between the three positions.
MacConaill did not mention any talar translations.

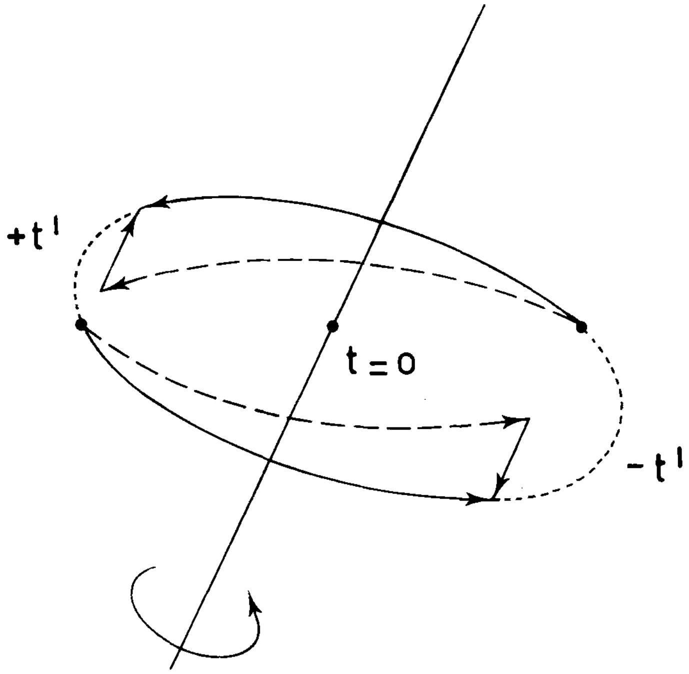

Figure 10-5. Relation of the distance between a point of contact and the rotation axis with the magnitude of displacement.

10.2.3 Directions and positions of talar axes, total range

Figure 10-9 shows among other things the three projections of the single absolute talar helical axis as computed for the total movement of preparation nr. 1.

Combining the three projections, we find the talus in relation to the fixed coordinates appears to rotate round one axis situated outside the talus, posteromedially to it, which axis passes through the posterior calcaneal process, in a very steep position, with a direction from anteromediosuperior to posterolateroinferior. This position of the axis matches a typical abduction movement of the talus combined with a small eversion component.

1. The deviation angles, π TA 30°/35° for all 10 preparations (Table 10-17)
This angle varied, taking into account the left-right difference from 48° to 75.7°. The mean angle of deviation was 62.2°; range 27.7°. In all preparations, the direction of the axis in relation to the sagittal plane was similar, viz. from anteromedial to posterolateral.

2. The inclination angles, φ TA 30°/35° for all 10 preparations (Table 10-17)
These varied from 66.6° to 86.6°. The mean inclination angle was 76.8°, range 20°.

Table 10-17. Talar deviation angles (π TA 30°/35°) and inclination angles (φ TA 30°/35°) total range.

Specimen	TA π 30°/35°	TA φ 30°/35°
1 R	63.8°	75.2°
2 R	58.4°	79.4°
3 R	66.0°	71.4°
4 R	55.8°	82.6°
5 R	75.7°	66.6°
6 R	66.9°	69.0°
7 R	56.1°	88.6°
8 L	- 66.2° (246.2°)	68.1°
9 L	- 65.5° (299.5°)	85.1°
10 L	- 48.0° (312.1°)	84.0°

Just as for the deviation, the direction of the axis was similar in all preparations, viz. from anterosuperior to posteroinferior in relation to the basal plane.

10.2.4 Rotations and translations along talar axes, total range

2. The rotations, α TA 30°/35° (Table 10-18)
The lowest value of α in our series was 21.5° (preparation nr 7) and the highest, 33.2° (preparation nr 10). The mean value was 28.7°, range 11.7°.
The direction of the talar rotation was clockwise for the 7-right-sided preparations, viewed in the dorsoplantar direction, and counter-clockwise for the 3 left-sided preparations. Considering the direction and position of the absolute talar helical axes, this means a predominant abduction component of the movement combined with a small eversion component.

Table 10-18. Talar rotations (α TA 30°/35°) and translations (t TA 30°/35°) total range.

Specimen	TA α 30°/35°	TA t 30°/35°
1 R	31.1°	- 3.0 mm
2 R	32.0°	- 4.0 mm
3 R	32.1°	- 3.7 mm
4 R	28.2°	- 2.5 mm
5 R	29.7°	- 4.6 mm
6 R	29.8°	- 3.6 mm
7 R	30.3°	- 1.7 mm
8 L	21.5°	- 8.2 mm
9 L	28.8°	- 0.1 mm
10 L	33.2°	- 1.2 mm

2. The translations, t TA 30°/35° (Table 10-18)
The translations t varied from 0.1 mm to 8.2 mm. The mean translation was 3.3 mm.
The direction of the translation was negative for all preparations, i.e. the talus moved towards the origin and underwent translation in the posterolateroinferior direction.

3. Comparison with the literature
Only a few authors have described the talar movement in closed kinematic chains, rendering possible a comparison with our data.
Huson (1961) described a combined abduction-eversion movement of the talus during tibial laterorotation. According to him, from the neutral 'intermediate position' the possibilities of adduction of the talus are only minimal. Hlavac (1967) in his study described the talar movement for the passage from maximal supination to pronation in the closed kinematic chains as follows: "The talus moves anterior, plantar flexes and adducts". These findings are in accordance with our data. From the neutral position to maximal supination, namely, we found a talar movement in the posterior direction and an extension with abduction. Hlavac investigated 'the angle of declination of the talus, that is the index of decrease in pitch of the talus toward the weight-supporting plane'. Hlavac's figures show that he refers to a symmetry line passing through the talar neck and head. According to Hlavac, the lateral roentgenograms showed an increase of the angle of declination for the passage from supination to intermediate position, of 8° (from 13° to 21°); for the passage from intermediate position to maximal pronation, the increase was 14.5° (from 21° to 35.5°).
Hlavac in presenting these talar data mentioned that it was difficult to carry out accurate measurements of the angle of declination, mostly because of the blurred projection of the lower edge of the talar head. This limited him to estimate the angle. It will be clear that in this manner, an exact computation of the talar movement will never be possible.

Kapandji (1970) reported a skiagraphic study of the changes of talar position for the passage from maximal eversion to maximal inversion. Kapandji states nò rotations in degrees for the talus. However, in his figures we constantly find a difference between the eversion and inversion outlines of the talus.

Ambagtsheer (1976) in a skiagraphic study of the tarsal translations from the starting position to 'incomplete supination', found an 'absolute' talar rotation of 23° in the horizontal projection, of 1° in the sagittal projection and of 1° in the frontal projection. The direction of rotation corresponded to abduction, extension and eversion. This is in agreement with our findings.
Ambagtsheer did not determine any absolute talar translations.

10.3 ABSOLUTE CALCANEAL MOVEMENTS

10.3.1 Directions and positions of calcaneal axes, partial range

The absolute calcaneal helical axes decribe the movements of the calcaneus in relation to the system of axes with origin 0 in the cage. To begin with, the results of preparation nr 1.
Figures nrs. 10-6a, 10-6b and 10-6c show the dorsal, frontal and sagittal projections, respectively, of this bundle of axes. The conclusion from these projections is that the bundle passes through the *inferoposterior portion of the tuber calcanei, with a direction from anterolateroinferior to posteromedio-superior.*
In the course of the standard movement, the calcaneus tilts from its medial to its lateral tubercle and back. Considering the axial directions, exorotation of the tibia is associated with a combined inversion-abduction movement, with a slight extension component. During this movement, the anterior calcaneal process describes the largest displacement and the (inferior) tubercle the smallest.

1. The deviation angles, π CA 10°, without phase 1, for all 10 preparations (Table 10-19)
The deviation angles did not vary much. Taking into account the left-right difference, π varied from -30.7°, to 10.9°. The mean value of each preparation varied from -22.7° to 5.5°.
In other words, the absolute calcaneal helical axes always made a small acute angle with the longitudinal axis of the foot.
In 8 of the 10 preparations (nrs 1, 2, 3, 4, 5, 6, 8 and 10), the absolute calcaneal helical axis alternatingly moved from posteromedial to posterolateral and from posterolateral to posteromedial. In *2 of the 10 preparations* (nrs 7 and 9), there was a permanent movement of the axis from posterolateral to posteromedial.

2. The inclination angles, φ CA 10°, without phase 1, for all 10 preparations (Table 10-20)
In all phases in all 10 preparations there was a similar direction of the axis, from *anterioinferior to posterosuperior,* with a fairly wide angle open to posterior.
The inclination angle varied from -17.3° to -71.5°. *The mean value for each preparation varied from -25.6° to -60.0°.*

In 8 of the 10 preparations (nrs 1, 2, 3, 4, 5, 6, 7, 9 and 10), φ showed a gradual increase, sometimes after an initial decrease. In other words, the axis turned to a steeper angle. *In 2 preparations* (nrs 5 and 8), φ decreased. When we combine the deviation and inclination data of the axes, the axial direction in 7 of the 10 preparations is always from anterolateroinferior to posteromediosuperior. In 3 preparations (nrs 2 and 7 for all phases, nr 4 only in the last four phases), the axial direction, on the other hand, is from anteromedioinferior to posterolatero-superior.

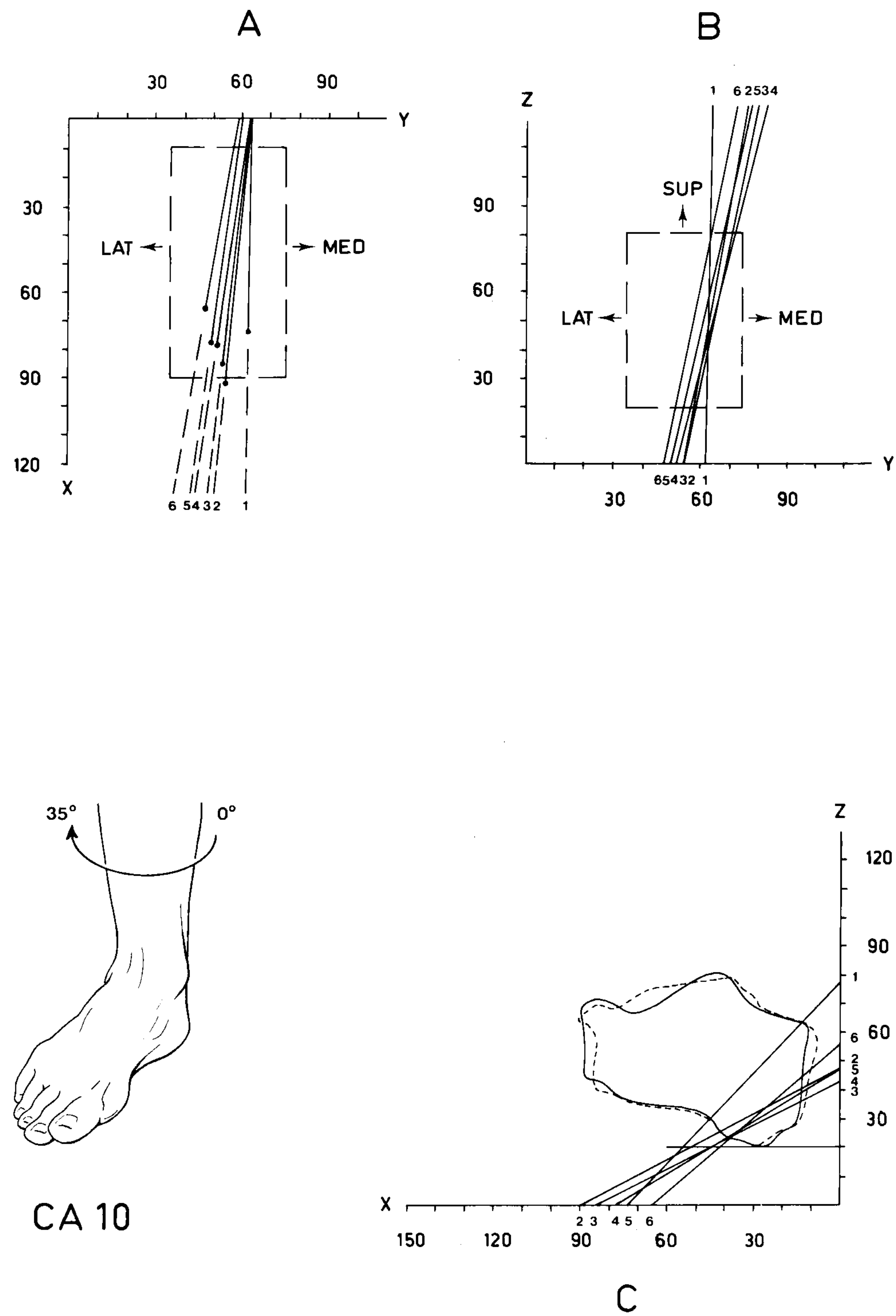

Figure 10-6. Projections of absolute calcaneal helical axes, CA 10°. Partial range 10°.

Table 10-19. Deviation angles of calcaneal axes (π CA 10°) with summation, mean and range of deviation angles.

Specimen	R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10
Phase										
1	179.0	186.9	148.1	166.2	169.6	166.6	197.2	196.0	187.8	186.7
2	-5.2	3.2	-25.6	-8.8	-14.7	-20.1	10.9	10.6	9.6	8.3
	(174.8)	(183.2)	(154.4)	(171.2)	(165.3)	(159.9)	(190.9)	(190.6)	(190.6)	(188.3)
3	-6.4	3.7	-14.3	0.1	-15.7	-13.7	7.0	5.5	17.0	7.2
	(173.6)	(183.7)	(165.7)	(180.1)	(164.3)	(166.3)	(187.0)	(185.5)	(197.0)	(187.2)
4	-8.1	3.5	-9.7	3.6	-11.9	-10.6	4.8	4.2	26.0	6.0
	(171.9)	(183.5)	(170.3)	(183.6)	(168.1)	(169.4)	(184.8)	(184.2)	(206.0)	(186.0)
5	-7.9	4.4	-10.7	3.4	-5.7	-11.4	4.7	5.8	30.4	4.8
	(172.1)	(184.3)	(169.3)	(183.4)	(174.3)	(168.6)	(184.7)	(185.8)	(210.4)	(184.8)
6	-9.9	7.3	-12.6	0.1	-4.4				30.7	0.4
	(170.1)	(187.3)	(167.4)	(180.1)	(175.6)				(210.7)	(180.4)
$\Sigma\ \pi$	-37.5	22.1	-72.9	-1.6	-52.4	-55.8	27.4	26.1	113.7	26.7
$\bar{\pi}$	-7.5	4.4	-14.6	-0.3	-10.5	-11.2	5.5	5.2	22.7	5.3
R π	4.7	4.1	15.9	12.4	11.3	9.5	6.2	6.4	21.1	7.9

Table 10-20. Inclination angles of calcaneal axes (φ CA 10°) with summation, mean and range of inclination angles.

Specimen	R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10
Phase										
1	-46.5	-14.4	-56.8	-52.8	-31.3	-36.2	-33.4	-65.0	-49.6	-57.2
2	-27.5	-17.3	-35.0	-28.8	-32.2	-30.6	-34.4	-46.0	-54.2	-53.0
3	-26.8	-28.0	-22.9	-17.5	-31.8	-30.0	-36.4	-30.3	-59.5	-51.8
4	-30.4	-41.4	-22.1	-25.3	-25.5	-31.6	-41.7	-23.9	-62.5	-53.8
5	-31.4	-55.0	-33.3	-38.1	-17.8	-39.2	-42.9	-29.5	-62.8	-61.2
6	-40.4	-57.4	-50.4	-41.4	-21.5				-60.8	-71.5
$\Sigma\ \varphi$	-156.2	-199.1	-163.7	-151.1	-128.8	-131.4	-155.4	-129.7	-299.8	-291.3
$\bar{\varphi}$	-31.2	-39.8	-32.7	-30.2	-25.6	-32.9	-38.9	-32.4	-60.0	-58.3
R φ	13.3	40.1	28.3	23.9	14.4	9.2	8.5	22.1	8.6	19.7

3. The angles $R\pi$ and $R\varphi$ of the bundle width, the bundle angle (Table 10-19, 10-20)
The bundle angle for the deviation ranged from 4.1° to 21.1° ($R\pi$). In the 10 preparations, the angle *$R\varphi$ ranged from 8.5° to 40.1°*. The bundle angle for the inclination in 9 of the 10 preparations exceeded that for the deviation (with the exception of preparation nr 9). We found that a large angle $R\varphi$ is not necessarily associated with a large angle $R\pi$.

4. A possible explanation of the differences in the direction of the bundles of absolute calcaneal axes and the differences in the pattern of movement of the axes may be found in the starting position of the calcaneus. For instance, the calcaneus may be tilted in a varus-valgus position (talipes cavus and pronounced pes planus, respectively); also, its position may be steep or more horizontal. When the calcaneus is in an intermediate position and even more when it is in a valgus position, it rests on the medial tubercle. This being far larger than the lateral tubercle, the latter has no contact with the supporting surface. Given an axial direction from anterolateroinferior to posteromediosuperior, the calcaneus during tibial laterorotation will tilt from its medial to its lateral tubercle. Were the calcaneus to be supported only by its lateral tubercle, as it does in the varus position of the heel, it can tilt only round its lateral tubercle.
As mentioned, a starting position of the calcaneus in the experiment was found by first making a number of trial runs of the standard movement, specifically of the continuous movement.
When the calcaneus did not slip off over the emery paper, that position of the calcaneus and accordingly of the tibia as well was adopted as the starting position.
We found in preparations nrs. 2, 4 and 7 an absolute calcaneal helical axis with a direction from anteromediosuperior to posterolateroinferior. Accordingly, the absolute calcaneal helical axes and the absolute tibial helical axes here both have a direction of the deviation from anteromedial to posterolateral. In preparations nrs 1, 3, 5, 6, 8 and 10 there was also a similar direction of the deviation for the absolute calcaneal and the absolute tibial helical axes; in both, the direction of the deviation was from anterolateral to posteromedial.
It was only in preparation nr 9 and in the first few phases of preparation nr 4 that the correlation of similar directions of deviation was not encountered.

10.3.2 Rotations and translations along calcaneal axes, partial range

1. The rotations, *α CA 10°* (Table 10-21)
The absolute calcaneal rotation varied from 3.3° to 11.5°.
In 9 of the 10 preparations, the rotation gradually increased, and might or might not decrease in the last few phases. Interestingly, in one preparation, nr 7, the rotation gradually decreased (preparation with talipes cavus and steep calcaneus; direction of absolute calcaneal and tibial axes from anteromedial to

Table 10-21. Calcaneal rotations (CA α 10°) and translations (CA t 10°), partial range.

Specimen		R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10	
	Phase											
t	1	-0.1	0.1	0.1	0.0	0.3	0.0	0.1	0.2	0.1	0.2	CA mm
α		4.3	4.7	1.8	3.2	2.3	2.2	3.6	9.2	3.7	5.3	CA°
t	2	0.1	0.1	0.1	0.0	-0.2	-0.1	0.0	0.3	0.1	0.2	CA mm
α		5.3	6.4	4.7	7.2	4.5	5.4	5.2	7.0	4.2	6.2	CA°
t	3	0.2	0.2	0.0	0.1	-0.1	0.1	0.1	0.4	0.2	0.2	CA mm
α		5.4	7.0	7.6	11.5	6.3	7.7	4.9	9.1	4.5	6.4	CA°
t	4	0.4	0.4	0.0	0.1	0.1	0.1	0.2	0.2	0.4	0.3	CA mm
α		6.0	7.0	8.4	10.8	8.5	7.5	3.9	9.1	5.2	6.3	CA°
t	5	0.4	0.5	0.0	0.1	0.1	0.2	0.2	0.4	0.4	0.2	CA mm
α		6.4	6.4	7.0	7.8	10.6	5.9	3.3	6.6	5.9	5.9	CA°
t	6	0.4	0.2	0.1	0.4	0.1				0.4	0.3	CA mm
α		5.6	5.4	6.2	5.7	9.2				6.3	5.8	CA°

posterolateral). The direction of rotation was counterclockwise for the 7 right-sided preparations (viewed in the anteroposterior direction) and clockwise for the 3 left-sided ones.

In all preparations, the axial direction showed that the *calcaneus made a combined inversion-abduction movement.*

In 7 of the 10 preparations (nrs 1, 3, 5, 6, 8, 9 and 10) there was also a slight extension component, while in three preparations (nrs 2, 4 and 7) there was a slight flexion component.

2. The translations, t CA 10° (Table 10-21)

The translations varied from -0.2 mm to 0.5 mm.

No particular pattern could be observed as regards the magnitude of the changes of the absolute calcaneal translations. Just as in the case of the talus, large translations are not necessarily associated with large rotations.

Considering the axial direction, the direction of the translation was in nearly all phases from posterosuperior to anteroinferior; in other words, *the calcaneus moved away from the origin (slightly forward).* In only three cases was there a negative translation, with the calcaneus moving toward the origin (preparation nr 5, phases 2 and 3; preparation nr 6, phase 2).

3. Comparison of the literature

Comparison with data in the literature is possible in only one case, because only one authors has described the calcaneal movements in phases.

Mostly, a total range of motion was calculated by comparing a starting position

with an end position. Frequently, only rotations were measured. In addition, most studies have been made with a non-weightbearing lower leg/foot preparation, except in the studie of MacConaill whose results we shall discuss.
MacConaill (1945) in a weight-bearing preparation made a skiagraphic study of the movement from maximal adduction to maximal abduction of the leg (tilting of the leg due to increasing abduction in the hip). He distinguished three positions, viz. the starting position, moderate abduction and nearly extreme abduction. MacConaill did not report the rotation quantatively, but described only the direction. For the absolute calcaneal movement he observed a rotation in the sense of an eversion for both steps, between the three positions mentioned. From his drawing we deduce that in these two steps, the rotations will have been of approximately the same magnitude.

10.3.3 Directions and positions of calcaneal axes, total range

The single, discrete absolute axis of the calcaneal movement, calculated for the displacement from the starting to the end position, had a direction from anterolateroinferior to posteromediosuperior, passing through the postero-inferior part of the calcaneus (for the three projections, see Figure 10-9a, 9b and 9c).

1. The deviation angles, π CA 30°/35° (Table 10-22)
Taking into account the left-right difference, this angle varied from -21.5° to 9.4°. The mean angle of deviation was 6.4°; range 36.2°. ($\bar{\pi}$, irrespective of the sign: 3.4°)
In other words, there was no similarity of direction in relation to the sagittal plane. Eight times, a direction from anterolateral to posteromedial was found, and twice a direction from anteromedial to posterolateral (cf. partial range).

Table 10-22. Calcaneal deviation angles (π CA 30°/35°) and inclination angles (φ CA 30°/35°) total range.

Specimen	CA π 30°/35°	CA φ 30°/35°
1 R	- 6.6° (173.4°)	- 35.6°
2 R	+ 3.7° (183.7°)	- 35.7°
3 R	- 14.7° (165.3°)	- 35.6°
4 R	- 0.5° (179.5°)	- 31.3°
5 R	- 8.5° (171.5°)	- 25.4°
6 R	- 13.1° (166.9°)	- 34.4°
7 R	+ 9.4° (189.4°)	- 37.3°
8 L	+ 5.6° (185.6°)	- 37.3°
9 L	+ 21.5° (201.5°)	- 58.5°
10 L	+ 6.6° (186.6°)	- 59.5°

2. The inclination angles, φ CA 30°/35° (Table 10-22)
This angle varied from -25.4° to -59.5°. The mean inclination angle amounted to -39.1°. In all preparations, the axis had a φ-value corresponding to a direction from anteroinferior to posterosuperior.

10.3.4 Rotations and translations along calcaneal axes, total range

1. The rotations, α CA 30°/35° (Table 10-23)
The rotations varied from 11.7° to 24.2°; range 12.7°. The mean value of α was 18.8°.
The rotatory direction of the calcaneus in relation to the fixed coordinates was counterclockwise for the 7 right-sided preparations (viewed in the a-p direction) and clockwise for the 3 left-sided ones. Considering the position and the direction of the axis, the movement was a combined one of abduction and inversion.

2. The translations, t CA 30°/35° (Table 10-23)
The translations varied from 0.3 mm to 1.2 mm. The mean calcaneal translation amounted to 0.7 mm. The direction of translation was positive in all 10 preparations; the calcaneus moved along helical calcaneal axis to anteroinferior.

3. Comparison with the literature
A comparison with our data is possible only in those few cases in the literature in which the absolute calcaneal movements are described. Huson (1961) in the closed kinematic chain described an inversion movement of the calcaneus for the passage from the starting position to maximal supination, and an eversion movement of the calcaneus for the return from maximal supination to the starting position.
During the movement from the starting position to pronation only a minimal eversion of the heel was found to occur; it was rather an overextension. This was seen particularly clearly in case of an existing valgus position of the heel. The pronation took place only in the metatarsotarsal, not in the tarsal joints!
Hlavac (1967) reported that in a 'closed kinematic chain the calcaneus everts with pronation and the calcaneus inverts with supination'. In a test subject standing erect, the movement from supination to pronation was studied with the aid of roentgenograms of the foot.
Hlavac considered the "angle of inclination of the calcaneus c.q. the index of increase in pitch of the calcaneus above the weight-supporting plane". In his experiment, the lateral roentgenogram showed a decrease of the angle of inclination of the calcaneus, from 23° (supinatory position) through 20° (neutral position) to 17° (pronatory position). Hlavac used as his criterium the angle between a tangent at the lower outline of the calcaneus and the basal plane, in the

Table 10-23. Calcaneal rotations (α CA 30°/35°) and translations (t CA 30°/35°) total range.

Specimen	CA α 30°/35°	CA t 30°/35°
1 R	18.4°	0.7 mm
2 R	19.8°	1.2 mm
3 R	18.8°	0.3 mm
4 R	24.2°	0.7 mm
5 R	22.6°	0.3 mm
6 R	15.7°	0.3 mm
7 R	11.7°	0.3 mm
8 L	19.2°	0.8 mm
9 L	17.2°	1.1 mm
10 L	20.5°	0.9 mm

lateral projection. Because the calcaneus in reality makes a three-dimensional movement, Hlavac's data are difficult to interpret.

Kapandji (1970) by means of skiagraphy surveyed the rotations of the tarsal bones for the movement from maximal eversion to maximal inversion. He implanted one marking pin in the calcaneus. The angle between the projections of this moving pin in the starting position and in the end position was measured in dorsoplantar (horizontal), frontal and lateral skiagrams. In the dorsoplantar skiagram, Kapandji observed a rotation of 5°, with a rotatory direction in the sense of an *adduction*. In addition there was a slightly anterior movement of the calcaneus. In the frontal skiagram, 20° rotation was observed with a rotatory direction in the sense of an inversion (Kapandji: supination). "The calcaneus slides medially under the talus". In the lateral skiagram, 12° rotation was observed with a rotatory direction in the sense of extension; in his drawing, however, Kapandji indicates 10°, with a rotatory direction in the sense of flexion instead of extension! Kapandji's findings are distinctly contradictory to our own data. Unlike him, for the move from the starting position to maximal supination, we computed a combined abduction-inversion movement of the calcaneus and therefore, from the movement from maximal supination to the starting position, a combined adduction-eversion. There was hardly any further pronation of the calcaneus in the starting position.

Cobey in 1976 presented a description of a posterior roentgenographic technique of the foot. Using this technique, he was able to describe the calcaneal movements during weight-bearing for the displacement from maximal tibial exorotation to maximal tibial endorotation. With Cobey's posterior roentgenography technique, a point where the calcaneus makes contact with the basal plane is determined in a dorsofrontal roentgenogram of the heel.
The axis of symmetry in the longitudinal direction of the tibia was used as a reference. In a test subject with flexible collapsing flat feet with a very mobile

subtalar joint, he observed a 2 cm displacement of the point of contact in relation to the axis of symmetry in the valgus position.
Although Cobey recommended his method for the study of subtalar motion, it only affords some insight into the purely calcaneal movements! If the talus were to remain fixed with complete rigidity, the method might indeed constitute a (rough) measure of the subtalar motion.

In the skiagraphic study of the tarsal movements made by Ambagtsheer (1976) we found, for the shift from the starting situation to 'incomplete supination' an absolute calcaneal rotation of 10° in the horizontal projection, of 2° in the sagittal and of 8° in the frontal projection. The rotatory direction was in the sense of an abduction, extension and inversion (tilt in a lateral direction; supinatory tilt). These findings are not contradictory to our data.
N.B.: In Ambagtsheer's experiments, the calcaneus was not fully fixed. The calcaneus had freedom to tilt with its tuberosity on a short fixation pin mounted on the floor plate of his experimental set-up. "The calcaneus could not roll sideways but only tilt."

10.4 ABSOLUTE NAVICULAR MOVEMENTS

10.4.1 Directions and positions of navicular axes, partial range

The absolute navicular helical axes describe the movements of the navicular bone in relation to the fixed system of axes of the cage.
First, the results of preparation nr 1.
In the dorsoplantar projection (Figure 10-7a), the axes projected laterally to the projected navicular bone in the starting position, and over the lateral part of the navicular bone in the end position. The direction of the axes is from anterolateral to posteromedial. In the frontal projection (Figure 10-7b), the axes are projected obliquely over the lateral half of the calcaneal framework. The direction of most axes is from laterosuperior to medioinferior.
Figure 10-10c shows the sagittal projection. The projection of the bundle of axes is inferior to the projected navicular bone and almost entirely inferior to the calcaneal tuberosity. The direction of the more or less horizontal axes is from anterosuperior to posteroinferior.

As appears from the combination of the three projections, the navicular bone moves round axes that nearly always run lateroinferiorly to the navicular bone in a direction from anterolaterosuperior to posteromedioinferior. Given a counter-clockwise rotation (viewed in the a-p direction), this results predominantly in an inversion movement. Since the predominantly longitudinally oriented axis (axes) is (are) situated outside the bone, viz. lateral to and below the navicular bone, this bone during inversion moves as a whole in the lateral and superior direction, through a certain angle. Therefore, for this movement we might also speak of an

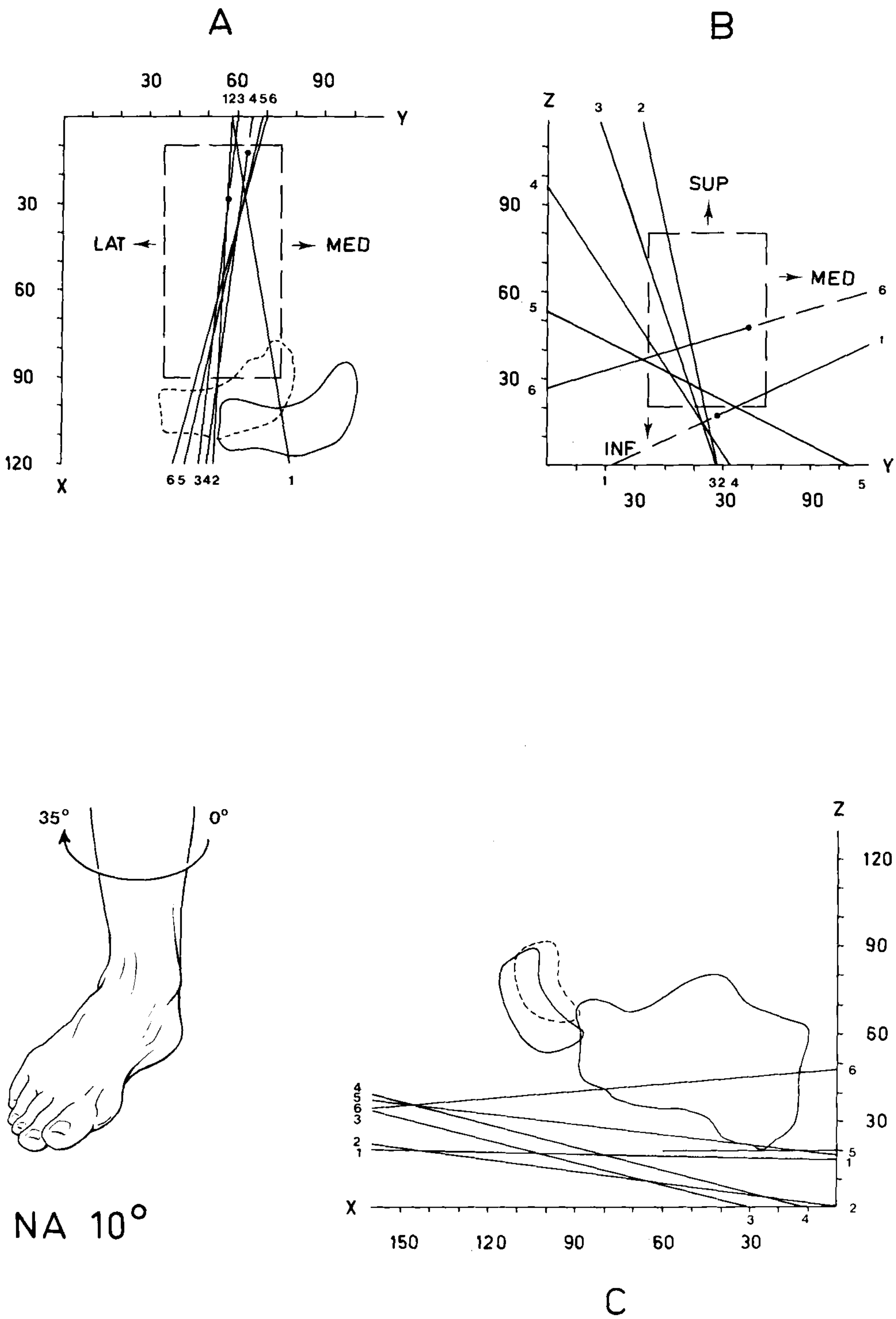

Figure 10-7. Projections of absolute navicular helical axes, CU 10°. Partial range.

Table 10-24. Deviation angles of navicular axes (π NA 10°) with summation, mean and range of deviation angles.

Specimen	R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10
Phase										
1	3.0	3.6	207.7	183.6	3.4	356.0	359.5	184.9	5.6	6.7
2	-2.5 (357.5)	-2.2 (357.8)	2.9	-3.4 (176.6)	-0.8 (179.2)	-9.6 (350.4)	-2.7 (357.3)	15.5 (190.5)	13.3 (193.3)	8.2
3	-4.7 (355.3)	-2.7 (357.3)	-6.0 (354.0)	-3.7 (356.3)	-0.2 (359.8)	-11.9 (348.1)	-7.5 (352.5)	11.7	20.5 (202.5)	11.0
4	-8.6 (351.4)	1.2	-8.4 (351.6)	-2.5 (357.5)	-2.2 (357.8)	-12.1 (347.9)	-9.2 (170.8)	12.0	28.4 (208.4)	13.5
5	-12.2 (347.8)	-3.2 (356.8)	-9.3 (350.7)	-4.6 (355.4)	-7.9 (352.1)	-12.4 (347.6)	-7.9 (172.1)	16.3 (196.3)	28.6 (208.6)	14.8
6	-14.9 (165.1)	-3.7 (356.3)	-9.8 (170.2)	-7.7 (352.3)	-12.0 (348.0)				28.6 (208.6)	17.9 (197.9)
$\Sigma\ \pi$	-42.9	-10.6	-30.6	-21.9	-23.1	-46.0	-27.3	45.5	119.4	65.4
$\bar{\pi}$	-8.6	-2.2	-6.2	-4.4	-4.6	-11.5	-6.8	11.4	23.9	13.1
R π	12.4	4.9	12.7	5.2	11.8	2.8	6.5	4.6	15.3	9.7

Table 10-25. Inclination angles of navicular axes (φ NA 10°) with summation, mean and range of inclination angles.

Specimen	R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10
Phase										
1	1.4	13.7	5.3	15.9	10.1	1.6	7.3	17.2	4.5	0.8
2	11.1	16.0	4.9	2.8	- 0.3	6.1	13.8	-6.9	-0.7	6.3
3	14.1	20.9	7.7	3.9	2.2	6.9	10.9	1.3	-8.6	10.8
4	13.2	25.0	10.7	8.5	8.1	8.2	-1.8	2.2	-17.5	10.8
5	6.2	18.8	7.7	6.2	10.0	10.8	-11.6	-9.9	-28.0	3.7
6	-4.2	0.1	-2.8	-5.5	6.4				-34.8	-10.9
$\Sigma\ \varphi$	40.8	80.8	28.2	15.9	26.4	32.0	11.3	-13.3	-89.6	20.7
$\bar{\varphi}$	8.1	16.2	5.6	3.2	5.3	8.0	2.8	-3.3	-17.9	4.1
R φ	18.3	24.9	13.5	14.0	10.3	4.7	25.4	12.1	34.1	21.7

abduction component combined with an extension component. In addition, the extension component is increased slightly by the transverse directional component of the absolute axis situated below and behind the navicular bone.

1. The deviation angles, π NA 10°, without phase 1, in all 10 preparations (Table 10-24)

In nearly all phases, the axial direction was from anterolateral to posteromedial. There were only two exceptions: preparation 2, phase 4 and preparation 3, phase 2 with axial direction from anteromedial to posterolateral. Taking into account the left-right difference, π varied from -28.6° to a maximum of 2.9°. The mean value for each of the preparations varied from -23.9° to -2.2°. In other words, the NA 10°-axes were always at an acute, fairly narrow angle with the longitudinal axis of the foot.

In 8 of the 10 preparations (nrs 1, 3, 5, 6, 7, 8, 9 and 10), the axis moved away from the sagittal plane. In 2 preparations (nrs 2 and 4), the axis when halfway turned back to the sagittal plane.

2. The inclination angles, φ NA 10° without phase 1 in all 10 preparations (Table 10-25)

In 9 of the 10 preparations, in most phases an axial direction from anterosuperior to posteroinferior was observed; this made an anteriorly open angle with and above the XY-plane. The inclination angle φ varied from -34.8° to 25.0°. The mean value for each of the preparations varied from -4.1° to 17.9°. Accordingly, the NA 10°-axes always were at a narrow angle to the basal plane. In 8 of the 10 preparations (nrs 1, 2, 3, 4, 5, 6, 9 and 10), we observed a gradual increase of the angle φ, which might or might not be associated with a decrease of φ in the last phase; in other words, the axis turned to a steeper angle. In preparations nrs 7 and 8, on the other hand, φ at first decreased and subsequently increased.

By combining the data on the deviation and inclination, we find in 9 of the 10 preparations for most phases an *axial direction from anterolaterosuperior to posteromedioinferior.*

The exception is preparation nr 9 in which the axial direction in all phases was from anteromedioinferior to posterolaterosuperior.

Changes of quadrant occurred in 7 preparations; in 6 preparations (nrs 1, 3, 4, 7, 8 and 10) we saw a change of quadrant (from lateral to medial) in the last phase and/or the last phase but one, while in one preparation (nr 5), we saw a change of quadrant in the starting phase.

3. The angles Rπ and Rφ of the bundle width, the bundle angle (Tables 10-24 and 10-25)

The angle Rπ ranged from 2.8° to 15.3°. In the 10 preparations, the angle Rφ ranged from 4.7° to 34.1°.

10.4.2 Rotations and translations along navicular axes, partial range

1. The rotations, α NA 10°, without phase 1 (Table 10-26)
The rotation round the absolute navicular axes varied from 5.4° to 18.6°. The value of α was always less in the starting phase than in the subsequent phases. The rotatory direction was counterclockwise for the 7 right-sided preparations and clockwise for the 3 left-sided ones (viewed in the a-p direction). The positions of the axes show that in most phases, there was inversion of the navicular bone.

2. The translations, t NA 10° step size, without phase 1 (Table 10-26)
The absolute navicular translation varied from -1.6 mm to 0.7 mm. In most cases, the direction of the translation was towards the origin, in other words, postero-medial. In 6 of the 10 preparations (nrs 1, 2, 5, 6, 8 and 10) translations with a different direction were seen in the starting or end phases. In one preparation (nr 7), positive translations were seen in all phases.

Table 10-26. Navicular rotations (NA α 10°) and translations (NA t 10°), partial range.

Specimen		R	R	R	R	R	R	R	L	L	L	
		1	2	3	4	5	6	7	8	9	10	
	Phase											
t	1	-0.3	0.3	-0.6	-0.2	0.2	0.4	0.3	-0.1	-0.3	-0.6	NA mm
α		4.5	6.0	1.3	4.5	2.4	4.0	5.5	5.3	6.6	8.2	NA°
t	2	-0.1	0.7	-0.5	-0.2	-0.2	0.4	0.1	0.3	-0.2	-0.8	NA mm
α		6.1	9.7	5.4	11.2	5.4	9.9	8.2	9.4	9.0	9.6	NA°
t	3	-0.2	0.5	-0.2	-0.6	-0.8	0.2	0.4	0.2	-1.1	-0.7	NA mm
α		6.4	9.7	11.5	18.1	8.0	14.9	8.3	13.1	10.0	9.7	NA°
t	4	-0.2	-0.5	-0.1	-1.5	-0.9	0.0	0.5	-0.2	-1.6	-0.6	NA mm
α		7.5	8.0	13.1	17.1	12.7	14.6	8.1	14.7	9.2	9.4	NA°
t	5	-0.1	-0.1	-0.4	-1.0	0.1	-0.1	0.3	-0.3	-1.4	-0.4	NA mm
α		9.8	7.8	11.7	13.0	18.3	10.6	7.2	12.8	8.4	9.1	NA°
t	6	0.1	0.1	0.7	0.2	0.6				-1.1	0.4	NA mm
α		11.9	10.2	11.9	10.7	18.6				8.3	9.9	NA°

3. Comparison with the literature
With the exception of one study, we have found no data in the literature concerning the movements of the navicular bone in a number of phases. Regrettably, in MacConaill's skiagraphic study, no data on movement in phases of the navicular bone are included.

10.4.3 Directions and positions of navicular axes, total range

Figure 10-9 shows among other things the three projections of the discrete absolute navicular helical axis as computed for the total movement of preparation nr 1.
The combination of these three projections shows that this fairly horizontal axis runs from anterolaterosuperior to posteromedioinferior. Considering the direction of rotation, this is consistent with a predominantly abductory movement of the navicular in relation to the fixed system of axes.

1. Deviation angles, π NA 30°/35° for all 10 preparations (Table 10-27)
Taking into account the left-right difference, these varied from -2.4° to -23.0°. The mean deviation angle π amounted to -9.5°. In other words, in all preparations the directions in relation to the sagittal plane were similar.

2. The inclination angles, φ NA 30°/35° for all 10 preparations (Table 10-27)
These varied from 1.1° to 14.3°. The mean inclination angle φ was 6.4°. In all directions the axis has a value of φ that corresponds to a direction from anterosuperior to posteroinferior.

Table 10-27. Navicular deviation angles (π NA 30°/35°) and inclination angles (φ NA 30°/35°) total range.

Specimen	NA π 30°/35°	NA φ 30°/35°
1 R	- 9.5° (350.5°)	4.3°
2 R	- 2.4° (357.6°)	13.4°
3 R	- 7.0° (352.9°)	4.8°
4 R	- 3.6° (356.4°)	1.1°
5 R	- 6.7° (353.3°)	7.5°
6 R	- 10.6° (349.4°)	7.9°
7 R	- 6.5° (353.3°)	2.6°
8 L	+ 12.5° (192.5°)	5.9°
9 L	+ 23.0° (203.0°)	14.3°
10 L	+ 13.2° (13.2°)	2.3°

3. Comparison with the literature
No comparison was possible because what applied to the total single movement applies to the composite movement as well: no other authors have described axes of rotation in relation to a fixed reference.

10.4.4 Rotations and translations along navicular axes, total range

1. The rotations, α NA 30°/35° (table 10-28)
The value of α ranged from a minimum of 20.7° to a maximum of 39.6°. The mean value of α was 30.2°, range 18.9°.
The direction of the rotation of the navicular was counterclockwise (viewed in the a-p direction) for the 7 right-sided preparations and clockwise for the 3 left-sided ones. This means that the movement was largely one of inversion.

2. The translations, t NA 30°/35° (Table 10-28)
The translations t varied from -1.3 mm to 3.6 mm. The mean translation was 0.2 mm, range 4.9 mm. The direction of translation was positive in 6 preparations (nrs 1, 2, 5, 6, 7 and 9): in other words, the navicular bone moved away from the origin. In four preparations (nrs 3, 4, 8 and 10), on the other hand, the navicular moved in the posterior direction.

Table 10-28. Navicular rotations (α NA 30°/35°) and translations (t NA 30°/35°) total range.

Specimen	NA α 30°/35°	NA t 30°/35°
1 R	26.7°	0.0 (0.04) mm
2 R	29.0°	1.0 mm
3 R	30.0°	-1.1 mm
4 R	39.6°	-1.3 mm
5 R	36.7°	0.3 mm
6 R	29.3°	0.5 mm
7 R	20.7°	1.1 mm
8 L	30.6°	-0.7 mm
9 L	27.9°	3.6 mm
10 L	31.7°	-1.1 mm

3. Comparison with the literature
We have found only a few authors who supplied data on the navicular rotations for the movement from the starting to the end position. Huson (1961) in the lateral roentgenogram of the tarsus of a test subject who performed a movement similar to that in our experiments, described how the projection of the navicular in the dorsoplantar direction grew smaller and how the navicular tuberosity becamse visible 'outside' the navicular bone, for the movement from the starting position to maximal supination, as a combined inversion-adduction motion.

Hlavac (1967) compared the positions of maximal pronation and maximal supination. In the lateral roentgenogram of the tarsus of the weight-bearing foot he reported an increase of the 'height of the navicular' from 2.85 cm to 4.3 cm. By the 'height of the navicular' was meant the distance 'of the inferior surface in relation to the supporting surface'.

Kapandji (1970) implanted a marking pin in the navicular bone and in skiagrams he recorded the navicular movements, comparing the positions of maximal eversion and maximal inversion.
In the vertical skiagram (dorsoplantar projection), 'the calcaneus staying put', 5° adduction was observed. In the anteroposterior skiagram (frontal position) 'the talus taken to be stationary', there was 25° supination (inversion). In the lateral skiagram (lateral projection), a rotation of 45° was measured. Kapandji then deduces from his 'angular displacements' that the movement involved was an extension; his drawings, however, show clearly that on the contrary it was a flexion!

Ambagtsheer (1976) reported the following skiagraphic findings for the movement from the starting position to the 'incomplete supinatory position' of the foot during tibial laterorotation.
In the dorsoplantar skiagram, no rotation of the navicular bone was seen. In the frontal skiagram, 29° rotation in the sense of inversion was measured. In the lateral skiagram, 7° rotation in the sense of extension was measured.
Ambagtsheer described this movement as a 'supinatory rotation of the navicular combined with a shift of this bone in a cranial direction; the principal movement of the navicular is a supination in a frontal plane and there is only a slight deviation from this plane".

10.5 ABSOLUTE CUBOID MOVEMENTS

10.5.1 Directions and positions of cuboid axes, partial range

The absolute cuboid helical axes describe the movements the cuboid in relation to the fixed coordinates in the cage. First, the results of preparation nr 1. In the dorsoplantar projection (Figure 10-8a), the axes are projected medially to the projection of the cuboid in the starting position and medially over the projection of the cuboid in the other positions, with an axial direction from anterolateral to posteromedial. In the frontal projection, the axes are projected over the calcaneal tuberosity, with an axial direction from laterosuperior to medioinferior (Figure 10-8b).
Figure 10-8c shows the sagittal projection. The projection of the bundle of axes is situated almost entirely below the projected cuboid and calcaneal tuberosity. The direction of the virtually horizontal axes is from anterosuperior to posteromedioinferior.

Combining the three projections, we find that the cuboid moves round axes that nearly always run horizontally and below the cuboid, with an axial direction from anterolaterosuperior to posteromedioinferior. During a counterclockwise rotation (viewed in the a-p direction), these axial directions result in an inversion movement.

Table 10-29. Deviation angles of cuboid axes (π CU 10°) with summation, mean and range of deviation angles.

Specimen	R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10
Phase										
1	177.4	357.9	179.9	181.3	3.2	173.0	179.0	192.7	186.1	8.2
2	-5.5 (354.5)	0.5	-2.8 (357.2)	-2.2 (117.8)	-2.0 (358.0)	-10.2 (349.8)	-4.0 (356.0)	14.7 (194.7)	8.4 (188.4)	11.2
3	-7.5 (352.5)	3.5	-8.4 (351.6)	-5.9 (354.1)	-3.8 (356.2)	-14.7 (345.3)	-5.3 (354.7)	15.6 (195.6)	9.3 (189.3)	13.6
4	-10.6 (349.4)	-0.7 (359.3)	-9.6 (350.4)	-7.9 (352.1)	-3.5 (356.5)	-16.2 (343.8)	-5.9 (174.1)	16.1 (196.1)	7.7 (187.7)	15.6
5	-12.6 (347.4)	-3.8 (356.2)	-8.3 (351.7)	-7.6 (362.4)	-6.6 (353.4)	-13.5 (346.5)	-6.4 (173.6)	14.5 (194.5)	9.3 (189.3)	16.6
6	-12.6 (167.4)	-4.2 (355.8)	-8.6 (351.4)	-8.5 (351.5)	-7.5 (352.5)				16.5 (196.5)	18.6
$\Sigma\ \pi$	-48.8	-4.7	-37.7	-32.1	-23.4	-54.6	-21.6	60.9	51.2	75.6
$\overline{\pi}$	- 9.8	-0.9	- 7.5	- 6.4	- 4.7	-10.9	- 5.4	15.2	10.2	15.1
R π	7.1	7.7	6.8	6.3	5.5	6.0	2.4	1.6	8.8	7.4

Table 10-30. Inclination angles of cuboid axes (φ CU 10°) with summation, mean and range of inclination angles.

Specimen	R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10
Phase										
φ 1	1.3	14.6	1.9	5.8	10.9	1.2	3.0	12.5	1.5	3.2
φ 2	4.7	15.8	10.6	- 0.7	7.8	3.0	1.4	- 6.8	- 1.4	3.6
φ 3	6.0	22.3	10.6	0.8	5.2	2.6	3.6	- 1.2	- 2.1	7.0
φ 4	4.6	23.0	7.6	4.4	3.7	2.5	- 1.3	- 0.7	- 5.4	8.0
φ 5	2.9	16.0	4.8	7.8	2.7	4.4	- 6.6	- 4.5	-15.3	6.7
φ 6	- 1.3	6.5	0.8	1.2	0.2				-27.2	3.8
$\Sigma\ \varphi$	16.9	83.6	34.4	13.5	19.6	12.5	- 2.9	-13.2	-51.4	29.1
$\overline{\varphi}$	3.4	16.7	6.9	2.7	3.9	3.1	- 0.7	- 3.3	-10.3	5.8
R φ	7.3	16.5	9.8	8.5	7.6	1.9	10.2	6.1	25.8	4.4

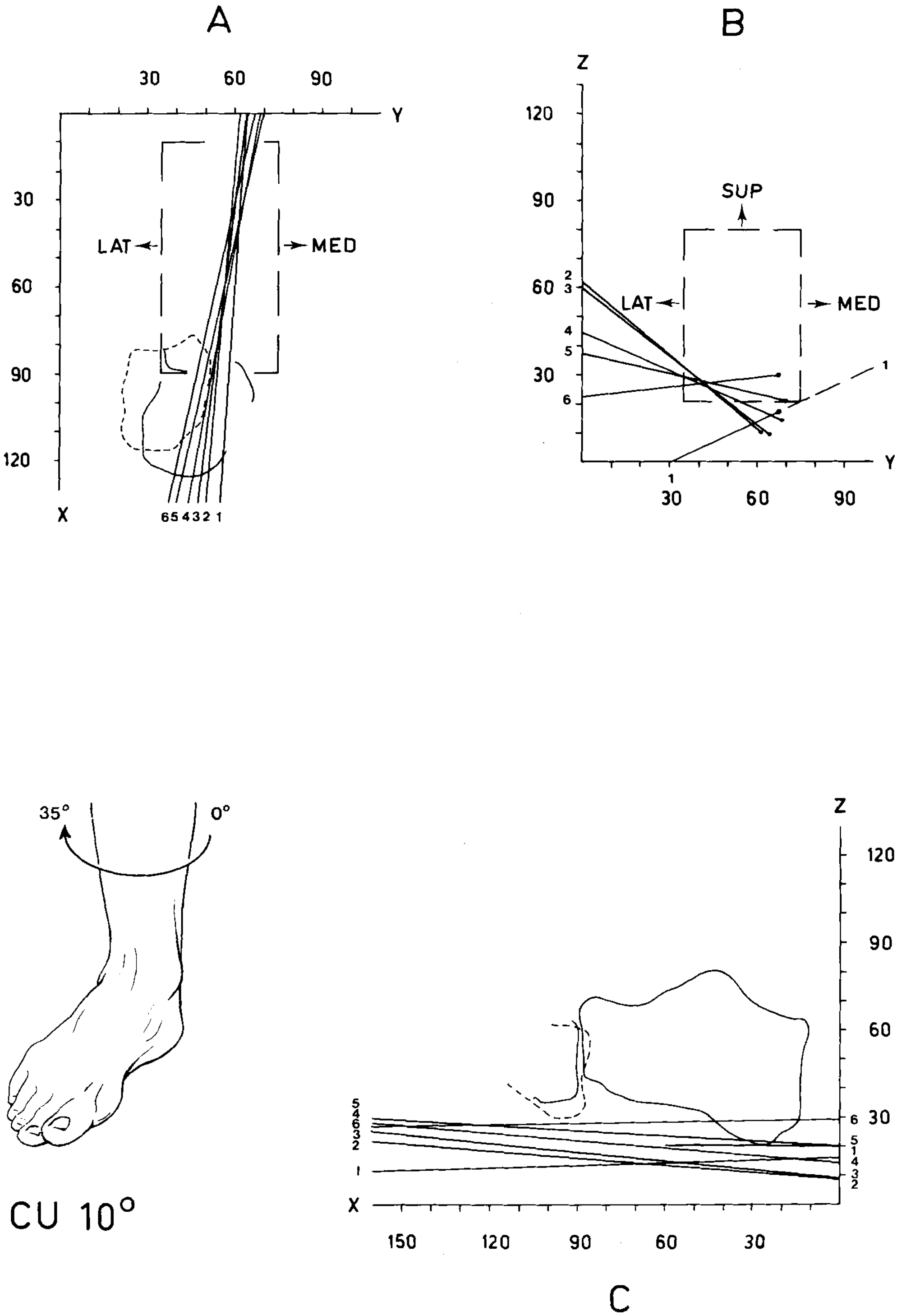

Figure 10-8. Projections of absolute cuboid helical axes, CU 10°. Partial range.

Just as in the case of the navicular, here, also, there is a slight abduction component and a very slight extension component.

1. The deviation angles, π CU 10°, without phase 1 in all 10 preparations Table 10-29)
In nearly all phases, an axial direction from anterolateral to posteromedial was found. In one preparation (nr 2) in phases 2 and 3 we observed an axial direction from anteromedial to posterolateral. Taking the left-right difference into account, π varied from -18.6° to 3.5°. The mean value for each of the preparations varied from -0.9 to -15.2°; range 14.3°. The CU 10° axes, accordingly, were always at a narrow, acute angle to the 'longitudinal axis' of the foot.
In all 10 preparations, a more or less gradual increase of π was seen. The movement in all cases was away from the sagittal plane.

2. The inclination angles, φ CU 10°, without phase 1 in all 10 preparations (Table 10-30)
In 8 of the 10 preparations (nrs 1, 2, 3, 4, 5, 6, 7 and 10), the axial direction was nearly always from anterosuperior to posteroinferior; only four times was an axial reversal observed in the starting and/or the end phase. In 2 preparations (nrs 8 and 9), the axial direction was from anteroinferior to posterosuperior in *all* phases. The inclination angle φ varied from -27.2° to 23.0°. The mean value for each of the preparations varied from -10.3° to 16.7°. In other words, the CU 10° axes were always at a narrow angle to the basal plane.
In 8 of the 10 preparations (nrs 1, 2, 3, 4, 6, 7, 8 and 10) there occurred a combination of increase of φ followed by a decrease, with the peak in a variable position. In 2 preparations, no such combination was seen: preparation nr 5 showed a constant decrease and preparation nr 9 a constant increase of φ.
Combining the data on the deviation and inclination, we find in 8 of the 10 preparations (nrs 1, 2, 3, 4, 5, 6, 7 and 10) virtually always an axial direction from anterolaterosuperior to posteromedioinferior. In 2 preparations (nrs 8 and 9), the axial direction was constantly from anterolateroinferior to posteromedio-superior.

3. The angles $R\pi$ and $R\varphi$ of the bundle width, the bundle angle. (Tables 10-29 and 10-30)
The angle $R\varphi$ ranged from 1.6° to 8.8°. In the 10 preparations, the angle $R\varphi$ ranged from 1.9° to 25.8°.

10.5.2 Rotations and translations along cuboid axes, partial range

1. The rotations, α CU 10°, without phase 1 (Table 10-31)
The rotations α round the absolute cuboid helical axis varied from 4.3° to 16.5°. The direction of the rotation was counterclockwise (viewed in the a-p direction)

Table 10-31. Cuboid rotations (α CU 10°) and translations (t CU 10°), partial range.

Specimen		R 1	R 2	R 3	R 4	R 5	R 6	R 7	L 8	L 9	L 10	
	Phase											
t	1	0.4	0.0	0.2	0.5	-0.3	0.1	-0.1	-0.2	-0.6	-0.8	CU mm
α		4.5	4.2	1.5	4.8	2.1	4.0	4.3	5.1	6.0	8.0	CU°
t	2	-0.2	-0.2	-0.5	0.6	-0.4	-0.4	-0.1	-0.5	-0.6	-0.8	CU mm
α		5.7	7.2	4.3	11.2	5.0	8.6	6.1	7.7	6.4	8.7	CU°
t	3	-0.2	-0.6	-0.4	-0.2	-0.5	-0.3	-0.3	-0.7	-0.5	-0.7	CU mm
α		6.3	7.1	7.5	16.5	8.2	11.2	5.6	10.4	5.5	8.6	CU°
t	4	-0.1	-0.3	-0.4	-0.6	-0.8	-0.2	0.1	-0.4	-0.4	-0.6	CU mm
α		7.3	6.8	9.5	14.6	11.3	10.2	4.8	11.6	5.1	7.9	CU°
t	5	-0.1	-0.2	-0.6	-1.1	-0.7	-0.3	0.1	-0.2	-0.2	-0.4	CU mm
α		8.5	7.2	9.6	11.1	12.8	6.7	4.3	8.3	5.3	6.8	CU°
t	6	0.3	-0.3	-0.7	-0.4	-0.8				0.2	0.0	CU mm
α		8.1	8.0	9.3	8.0	13.0				5.8	5.7	CU°

in the 7 right-sided, and clockwise in the 3 left-sided preparations.
The positions of the axes show that in most phases an inversion of the cuboid was involved; in addition there were slight abduction and extension components.

2. The translations, t CU 10°, without phase 1 (Table 10-31)
The absolute cuboid translations varied from -1.1 mm to 0.6 mm. The translation nearly always had a negative direction; in other words, the cuboid was translated along the helical axis in the direction of the origin.

3. Comparison with the literature
We have also studied MacConaill's data for the stepwise movements, but these proved not suitable for comparison with the stepwise movements carried out in our experiment.

10.5.3 Directions and positions of cuboid axes, total range

Figure 10-9 among other things displays the three projections of the discrete absolute cuboid helical axis as computed for the total single movement of preparation nr. 1.
Combining these three projections, we find that the direction of this axis is similar to that of the bundle of axes, viz. from anterolaterosuperior to postero-medioinferior with a nearly horizontal direction of the axis. Considering the direction of rotation, this position of the axis predominantly corresponds to an abduction movement of the cuboid in relation to the system of axes in the cage.

1. The deviation angles, π CU 30°/35° in all 10 preparations (Table 10-32)
Taking into account the left-right difference, this angle varied from -143° to -2.1°. The mean deviation angle π amounted to -8.6°: range 12.2°. In other words, the direction of the axis in relation to the sagittal plane was similar in all preparations.

2. The inclination angles, φ CU 30°/35° in all 10 preparations (Table 10-32)
These varied from 1.4° to 15.3°. The mean inclination angle φ was 5.1°; range 13.9°.
In all directions, the axis has a value of φ that corresponds to a direction from anterosuperior to posteroinferior.

Table 10-32. Cuboid deviation angles (π CU 30°/35°) and inclination angles (φ CU 30°/35°) total range.

Specimen	CU π 30°/35°	CU φ 30°/35°
1 R	- 9.3° (350.7°)	2.1°
2 R	- 2.1° (357.9°)	15.3°
3 R	- 8.2° (351.8°)	5.2°
4 R	- 5.4° (354.6°)	1.9°
5 R	- 5.4° (354.6°)	3.1°
6 R	- 12.7° (347.3°)	2.6°
7 R	- 4.4° (175.6°)	1.4°
8 L	14.3° (194.4°)	4.7°
9 L	10.7° (190.7°)	9.5°
10 L	13.2° (12.3°)	5.6°

3. Comparison with the literature
Since in this paragraph we consider the motion of the bone in maximal tibial laterorotation, we can attempt once more to make a comparison with the literature.
The literature contains no data on movements of the cuboid bone in relation to a fixed reference that allowed the calcaneus, also, to carry out its own movement. Admittedly, in the known studies by Fick (1904), Dönitz (1903), Manter (1941) and Elftman (1960), reference is constantly made to the movements of the cuboid bone in relation to a 'stationary element', but in these studies, the calcaneus is always fixed as the 'stationary element', in other words, the discussion is in reality about relative cuboid calcaneal movements and axes.

These authors, also, have failed to make clear in which active or passive way the cuboid was moved in relation to the fixed calcaneus. Where its direction is concerned, the axis of Dönitz and Fick for the relative cuboidcalcaneal movement mostly resembles the absolute cuboid helical axis found by us!

10.5.4 Rotations and translations along cuboid axes, total range

1. The rotations, α CU 30°/35° (Table 10-33)
The minimal value of α was 14.2°, the maximal value 35.0°, the mean value 23.8° and the range, 20.8°. The direction of rotation of the cuboid was counterclockwise (viewed in the a-p direction) in the 7 right-sided, and clockwise in the 3 left-sided preparations. This means that the movement was largely one of inversion.

2. The translations, t CU 30°/35° (Table 10-33)
The translations t varied from -2.1 mm to -0.2 mm. The mean translation was -1.1 mm and the range 1.9 mm.
In all 10 preparations, the translation of the cuboid was towards the origin, i.e. in the posterior direction.

Table 10-33. Cuboid rotations (CU α 30°/35°) and translations (CU t 30°/35°) total range.

Specimen	CU α 30°/35°	CU t 30°/35°
1 R	22.9°	- 0.8 mm
2 R	22.7°	- 0.7 mm
3 R	23.1°	- 1.5 mm
4 R	35.0°	- 1.2 mm
5 R	29.4°	- 1.6 mm
6 R	21.9°	- 0.8 mm
7 R	14.2°	- 0.2 mm
8 L	23.7°	- 0.9 mm
9 L	19.5°	- 0.8 mm
10 L	25.9°	- 2.1 mm

3. Comparison with the literature
Comparison with the literature is possible in only a few cases, because most authors supply no data on the absolute cuboid movements. Most authors have studied the maximal range of movement of a cuboid bone relative to a fixed immobile calcaneus.
This movement was then stated as a rotation through a number of degrees. The methods of study of most authors clearly show that they have examined the relative cuboid calcaneal movements.
It is only Kapandji (1970) and Ambagtsheer (1976) who have reported rotations in degrees for the absolute movements of the tarsal bones. Thus, Kapandji presents a survey of the rotations of tarsal bones studied by skiagraphy for the displacement from maximal eversion to maximal inversion. One marking pin was implanted per bone. According to Kapandji, in the dorsoplantar skiagram the

cuboid rotates 5° in the medial direction with a rotatory direction in the sense of an adduction. In addition, he mentioned a 'medial slide relative to the calcaneus'. In the frontal skiagram (talus stationary), there was a 18° supination (inversion). In the lateral skiagram he reports an extension of 12° but the drawing shows it was actually a flexion.
Examination of the drawings which Kapandji presents in his book 'Physiology of the human joints' shows that the position of the marking pin in the bone greatly affects the rotation computed!

Ambagtsheer in the horizontal plane found an absolute cuboid rotation of 1°, in the frontal plane an inversion of 14° in accordance with our findings, and in the sagittal plane, a rotation of 1°. Here, as well, the rotations found depended on the positions of the pins implanted. Mention should be made of the fact that Gamble on the basis of roentgenograms assigned certain rotations and/or translations to movements in the calcaneocuboid joint. However, he omitted any data concerning the magnitude of these rotations and/or translations. Thus, in his textbook 'Applied Foot Röntgenology' (1957), he writes that when there exists an 'outline step' between the cuboid and the calcaneal projection with an 'uneven articulation of facets', this typically corresponds to an 'everted position of the cuboid' and that in this everted position, the 'density or the peroneal groove is lost'.
According to our findings (see sagittal view, Figure 10-9c), this 'uneven articulation, on the contrary corresponds to supinatory configuration of the foot plate; in other words, to a typical inversion of the cuboid.

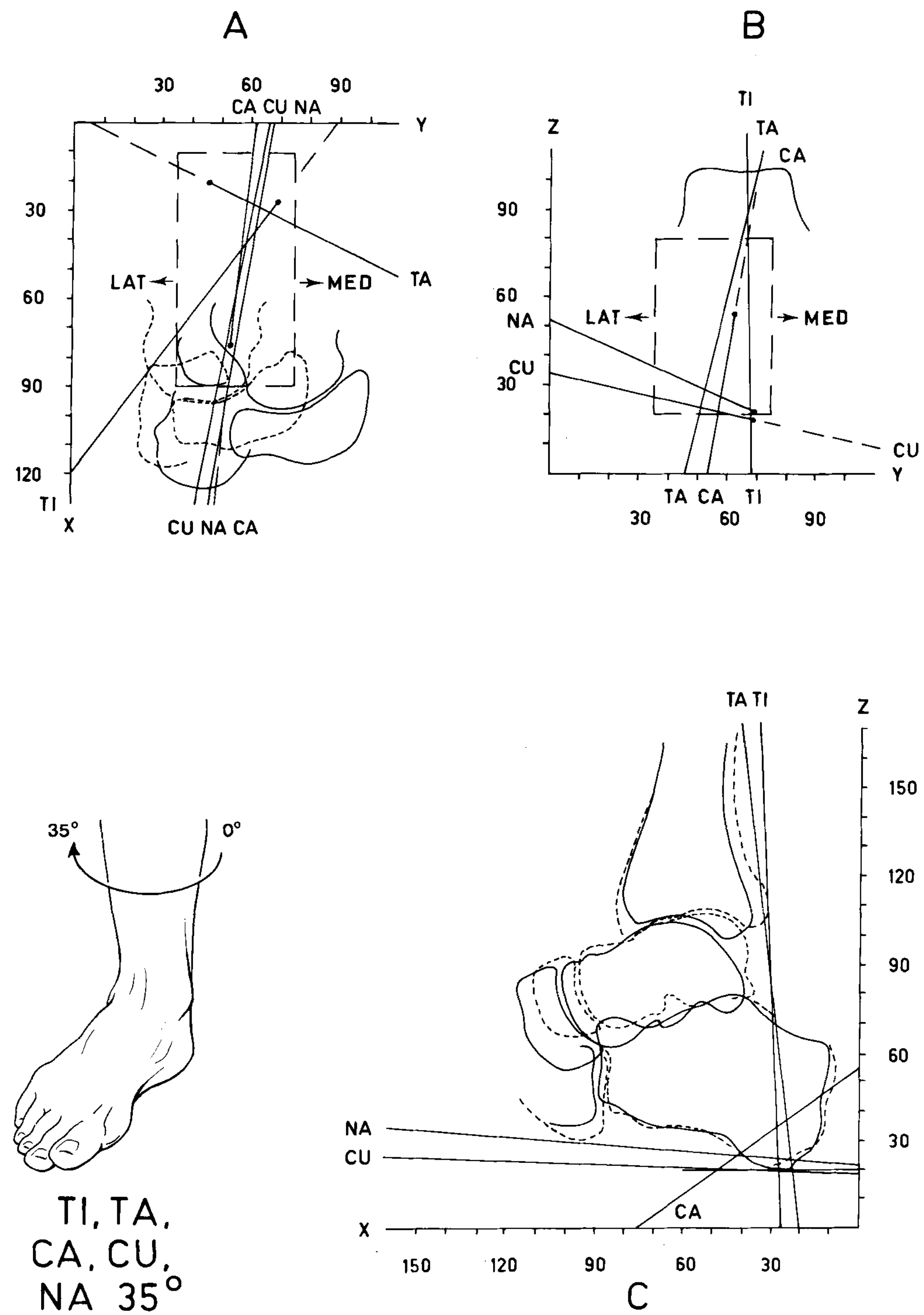

Figure 10-9. Projections of absolute tarsal (TA, 30°/35°, CA 30°/35°, NA 30°/35° and CU 30°/35°) and tibial (TI 30°/35°) helical axes, total range.