Assessment of hindfoot deformity by three-dimensional MRI in infant club foot

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In 12 infants aged under 16 months with unilateral club foot we used MRI in association with multiplanar reconstruction to calculate the volume and principal axes of inertia of the bone and cartilaginous structures of the hindfoot.

The volume of these structures in the club foot is about 20% smaller than that in the normal foot. The reduction in volume of the ossification centre of the talus (40%) is greater than that of the calcaneus (20%). The long axes of both the ossification centre and the cartilaginous anlage of the calcaneus are identical in normal and club feet. The long axis of the osseous nucleus of the talus of normal and club feet is medially rotated relative to the cartilaginous anlage, but the angle is greater in club feet (10° v 14°). The cartilaginous structure of the calcaneus is significantly medially rotated in club feet (15°) relative to the bimalleolar axis. The cartilaginous anlage of the talus is medially rotated in both normal and club feet, but with a smaller angle for club feet (28° v 38°). This objective technique of measurement of the deformity may be of value preoperatively.

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The term 'club foot' is used for a combination of bony deformities including medial deviation of the neck and head of the talus, and joint deformities (hindfoot equinus

and varus, forefoot adduction). Over the last few years, a large number of anatomical,¹⁻⁶ radiological,⁷ CT,⁸ three-dimensional (3D) computer modelling⁹ and MRI^{10,11} studies have been performed on this condition. Together with the surgical findings,¹² they have contributed much to the better understanding of this complex 3D deformity.¹³ Nevertheless, the position of the secondary ossification centres of the bones of the hindfoot, relative to their cartilaginous anlagen, and the position of the talus relative to the ankle, remain controversial. This is due to the lack of objective analysis of the deformity in infants. As a result, the surgical manoeuvres to reduce the interosseous deformities of the hindfoot are contradictory.^{1,2,12} In an attempt to contribute to this debate, we carried out MRI studies with 3D reconstruction over a period of one year. Using a computer software program we calculated the principal axes of inertia of each cartilaginous and bony structure, which corresponded to the 3D anatomical axes of the osseous and cartilaginous volumes. This allowed the measurement of the osseous and cartilaginous relationships.

Patients and Methods

We evaluated 12 patients with unilateral idiopathic club foot (Table I), 15 days before surgery. Their mean age was 11 months (9 to 16).

At birth, they had been classified according to their severity² by the senior author (JPC). There were seven cases of moderate club foot and five of severe.

From birth to preoperative assessment they had been treated by daily manipulation and splintage. This treatment failed to correct the deformity entirely. Applying Catterall's classification¹⁴ before surgery, we noted that 11 feet had a joint contracture combining a posterior deformity in the sagittal plane and a midtarsal deformity in the horizontal plane. One foot (case 1) had a false correction diagnosed by a preoperative radiograph.

We performed MRI under general anaesthesia. The feet were strapped to a vertical panel so that the soles were as close to a plantigrade position as possible. In some cases the whole of the sole could not be placed directly against the panel.

The method is based on the principle that for any 3D volume, a software program may calculate the centroid

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Table I. Details of the 12 patients with unilateral club foot

Case	Gender	Date of birth	Birth group	Preoperative assessment date	Preoperative dorsiflexion (degrees)	Preoperative forefoot adduction (degrees)
1	M	8.12.95	Moderate	30.9.96	+5	5
2	M	12.1.95	Moderate	27.11.95	-10	10
3	F	16.6.95	Moderate	29.4.96	0	15
4	M	3.10.94	Moderate	10.7.95	-15	25
5	M	12.2.96	Moderate	27.1.97	-5	15
6	M	10.11.95	Moderate	24.3.97	0	5
7	M	2.3.95	Moderate	24.2.97	0	10
8	F	12.1.95	Severe	11.12.95	-5	5
9	M	15.10.94	Severe	10.8.95	-10	10
10	M	11.11.94	Severe	23.10.95	0	15
11	M	13.2.95	Severe	15.1.96	-30	25
12	F	28.4.96	Severe	17.3.97	0	5

(mass centre) of this volume and the principal axes of inertia which pass through the centroid. These axes, which correspond to the principal moments of inertia, are defined as the long, medium and short axes of this volume, and they also correspond to its anatomical axes in a 3D analysis. Johnston et al⁸ reported that these computer axes differ from any geometrical axes which may be found by traditional orthopaedic methods. A previous study has shown that this technique is reliable and reproducible.¹⁵

The following steps were used to obtain this 3D analysis. First, MRI (Siemens Magnetom Vision, 1.5 Tesla; Siemens, Erlangen, Germany) allowed a volumetric assessment, selecting a volume of which the length was between 180 and 220 mm according to the foot size. Multiplanar reconstruction allowed this volume to be divided into between 40 and 60 1 mm thick slices parallel to the plantar plane. The pixel matrix size was 512×512 , while the resolution of the pixel was about 0.4. Secondly, a software program developed in our laboratory (SIP 305, copyright INSERM), allowed the initial decoding of the MR scan, the detection of the contour of the region of interest, and the transfer of these data into a graphic workstation (Silicon Graphics, Mountain View, California). Thirdly, using the graphic workstation, the 3D geometry of each bone was obtained by connecting the different sections. The visualisation of the geometrical model of the foot was obtained by a pre- and postprocessing software Patran (MSC Nastran Corporation, Los Angeles, California). The geometrical centre (centre of mass with unit mass) and the principal axes of inertia (with unit mass) were calculated for each bone (Fig. 1). The long, medium and short axes thus defined correspond to the anatomical axes.

This method allowed three measurements to be obtained: 1) the volume of each bone in the hindfoot; 2) the intra-osseous relationships which were quantified by the angle between the long axes of the cartilaginous and osseous structures of the bones of the hindfoot (Fig. 2); and 3) the interosseous or intercartilaginous relationships which were defined by the angle between the long axis of the bone of interest and the bimalleolar axis. By convention, as in the studies performed by Herzenberg et al⁹ and Downey, Dren-

nan and Garcia,¹⁰ the bimalleolar axis was used as the reference line. The values were found by measuring the angles between the axes of the different bones in the anteroposterior (AP) and lateral views.

Finally, statistical analysis (paired Student's *t*-test) using the SYSTAT programme (Evanston, Illinois) allowed comparison of the angles in the normal (contralateral) foot and the club foot.

Results

Volume measurements. The volume of both the bone and cartilaginous structures was smaller in the club foot (Table II). The reduction in volume for the cartilaginous anlage was 24% for the talus and 21% for the calcaneus. The

Fig. 1

The principal axes of inertia pass through the mass centre of any bone volume. They are defined as the long axis (1) which corresponds to the minimum moment of inertia, the short axis (2) which corresponds to the maximum moment of inertia (perpendicular to the long axis) and the medium axis (3) which is perpendicular to both the long and short axes. (with permission Hobatho et al¹⁵).

Fig. 2

The intraosseous relationships of the talus. Note the angle between the long axes of the osseous and cartilaginous structures in the left club foot and right normal foot rotated through 180° to allow a direct comparison of the axes.

Table II. Measurement of the volume (mm^3) of the talus and calcaneus in normal feet and in club feet

	Volume				Reduction in volume (%)
	Normal		Club feet		
	Mean	SD	Mean	SD	
Talus (bone)	1460	481	855	272	41
Talus (cart)	3445	903	2622	1160	24
Calcaneus (bone)	2467	571	1983	448	20
Calcaneus (cart)	5278	1266	4177	1096	21

Table III. Angular difference (degrees) between the longitudinal axes (Z) of the cartilage anlage and the osseous nucleus of the talus and calcaneus in club feet and normal feet

AP	Normal		Club feet	
	Mean	sd	Mean	sd
Bone-cart				
Ztal	10	4.5	14.5	5
Zcal	2	2	2	2

Table IV. The internal rotation (degrees) of the longitudinal axes (Z) for bone and cartilage in the talus and calcaneus relative to the bimalleolar axis of the ankle

AP	Normal		Club feet	
	Mean	sd	Mean	sd
Ztal/Ref (bone)	46.5	11	42	9
Ztal/Ref (cart)	38	10	27	9
Zcal/Ref (bone)	1.5	9	15	7
Zcal/Ref (cart)	3	10	15	5

volume reduction for the osseous nucleus was 41% for the talus and 20% for the calcaneus.

Intraosseous relationships. In the AP view (Table III), the long axes of both the bone and cartilaginous structures of the calcaneus were identical for normal feet ($2 \pm 2^\circ$) and club feet ($2 \pm 2^\circ$). For the normal talus, the long axis of the

ossification centre was internally rotated ($10 \pm 4.5^\circ$) relative to the long axis of its cartilaginous structure. In the club foot talus, there was an increased medial rotation of the osseous nucleus ($14.5 \pm 5^\circ$) relative to its cartilaginous structure. The difference between these values was not statistically significant ($p > 0.05$).

Table V. Talocalcaneal angles (degrees) for bone and cartilage in the AP and lateral planes in club feet and normal feet

	Normal		Club feet	
	Mean	SD	Mean	SD
AP				
Ztal/Zcal (bone)	47	10	28	9
Ztal/Zcal (cart)	36	10	13	9
Lateral				
Ztal/Zcal (bone)	31	15	9	8
Ztal/Zcal (cart)	22	10	7	6

Interosseous relationships. The long axis of the normal talus relative to the bimalleolar axis of the ankle was internally rotated by $38 \pm 10^\circ$ for the cartilaginous anlage and by $46.5 \pm 11^\circ$ for the ossification centre. In the club foot the internal rotation of the cartilaginous talus/bimalleolar angle was smaller ($27 \pm 9^\circ$) than in the normal foot, whereas the osseous talus/bimalleolar angle was approximately the same ($42 \pm 9^\circ$). For both the bone and cartilaginous structures of the calcaneus there was a slight medial rotation ($1.5 \pm 9^\circ$ and $3 \pm 10^\circ$, respectively), relative to the ankle mortise in normal feet, whereas these structures were significantly internally rotated in club feet ($15 \pm 7^\circ$ and $15 \pm 5^\circ$, respectively) (Table IV). In the AP and lateral views, the talocalcaneal angles of both the cartilaginous and the bone structures were smaller in club feet than in normal feet (Table V).

Discussion

The results of our study show a volume reduction of the hindfoot cartilaginous anlage in the club foot of about 20%. The 40% reduction in volume of the ossification centre of the talus was greater than that for the calcaneus. These results suggest that the club foot deformity affects the development of the talus more than that of the calcaneus. The present figures, however, cannot be directly compared with previous anatomical studies^{13,14} due to the difference in the age of the patients and the methods of measurement. Some of the controversial assumptions previously advanced to explain this impaired development have been reviewed by Howard and Benson.³ It has been proposed that the lack of growth of the ossification centre of the talus could be the result of either elevated extrinsic pressure or abnormal bone development.

Our study of the intraosseous relationships showed that the angles between the long axes (osseous and cartilaginous) of the calcaneus in normal feet were identical. For the normal talus, the long axis of the osseous nucleus was medially rotated ($10 \pm 4.5^\circ$) relative to the long axis of the cartilaginous anlage. Hubbard et al¹⁶ noted a difference in the orientation of the cartilaginous anlage of the talus relative to the osseous nucleus. Their study concerned normal patients aged from three months to seven years. In our patients, the intraosseous relationships were similar to those in the normal foot, with a slightly higher

medial deviation for the talus. This deviation was not statistically significant for the number of cases studied. More cases of club foot need to be studied to confirm these results.

The intercartilaginous relationships in club foot showed medial rotation of the calcaneus, relative to the bimalleolar axis. This result is similar to that found by Downey et al¹⁰ using MRI despite the difference in the method of calculation. It suggests that in order to reduce the deformity, the calcaneus should be externally rotated surgically in all cases of club foot, as reported in other studies.^{1,2,12,17}

Concerning the position of the cartilaginous talus in club foot relative to the bimalleolar axis, a smaller medial rotation (27°) was noted than in a normal foot, with a range of values between 16° and 36° . This result cannot be compared with other studies^{9,10} since the method which we used had only one axis to describe the 3D shape of the cartilaginous talus. This technique allowed a better visualisation of the position of the talus in the foot than may be achieved by using one axis for the body and another axis for the neck. These measurements suggest that the decision to rotate the talus medially will depend on the calculation of its position before surgery. These findings are in agreement with those of Carroll et al¹ and McKay,¹² but no indication of lateral derotation of the talus, as proposed by Goldner,² was found.

The technique allowed an objective quantification of club foot deformity based on a 3D description of the hindfoot bones. The intraosseous study demonstrated the difference in position of the osseous nucleus of the talus relative to the cartilaginous anlage. Our results show the limits of plain radiological measurement. The indication for a medial derotation of the talus depends on its preoperative position relative to the bimalleolar axis. A preoperative measurement of the position of the talus using MRI would appear to be useful.

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