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The mechano-biology of the epiphysis of the long bones as revealed by photoelastic models

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Summary

Stress contours have been generated in photoelastic models simulating cartilaginous and bony epiphyses. According to the findings, the secondary centre of ossification is formed in areas of the cartilaginous epiphysis shown to have reduced mechanical stress. The bony epiphysis appears to have been developed as a more mechanically efficient structure.

Keywords: *Mechano-biology, mechanical stimulus, cartilaginous epiphysis, bony epiphysis, photoelastic models.*

Resume

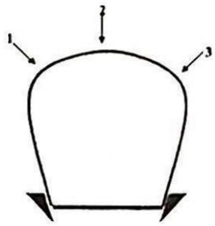
Des découpes d'effort ont été produites dans les modèles photoelastic simulant les epiphyses cartilagineux et osseux. Selon les résultats, le centre secondaire de l'ossification est formé dans les secteurs de l'epiphysis cartilagineux montré pour avoir l'effort mécanique réduit. L'epiphysis osseux semble avoir été développé comme structure plus mécaniquement efficace.

Introduction

The epiphysis of the long bones exists in two forms; namely, cartilaginous and bony. In embryonic and early post-natal life, it is made up of a solid mass of cartilage [1]. This is later converted into the bony epiphysis when its midsection breaks down, becomes vascularised and is then replaced with bone [2,3]. This is called the secondary centre of ossification developing after the primary centre from which much of the bone ossifies. The bony epiphysis has a cartilaginous shell of which the growth plate or physis is a part, an inner lining of bone and a core made up of marrow elements. The stimulus causing the internal remodelling of the cartilaginous epiphysis is not known with any certainty. The possibility that it could be a mechanical stimulus has been investigated in this study using photoelastic models.

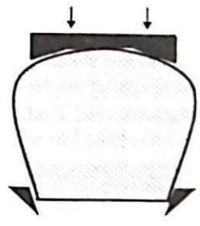
The velocity of light through a transparent body depends upon the stress level in that body. This is the basis of the photoelastic phenomenon. This phenomenon may be observed and quantified using an optical instrument called a polariscope. From such observations, it is possible to deduce the stress state of a transparent body [4]. The polariscope consists essentially of a light source and filter, a polariser which renders the incident light plane-polarised and a second polariser called the analyser. The photoelastic specimen or model is placed between the polariser and the analyser and viewed through the analyser.

Gebhardt [5] and Pauwels [6] used a photoelastic model to examine the relationship between stresses within the chondroepiphysis and formation of the secondary centre. The model was pushed into wedge-shaped grips simulating the diaphyseal tube (Figure 1a & 1b). Gebhardt (1911) [5] applied load at various points on the model to generate trajectories. These trajectories crossed in the central zone and he regarded this zone as area of greatest accumulation of stress, which induced bone to form. Pauwels (1980) [6] by contrast pressed a conforming contact surface against the model. He observed an area of low stresses just below the central zone and concluded that this was confirmatory evidence that the secondary centre is formed in areas of increased hydrostatic pressure.



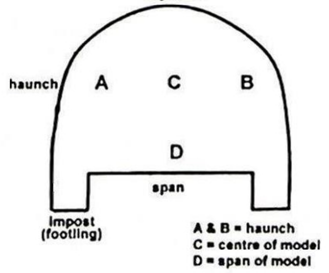
a) Gebhardt model

Fig. 1a:



b) Pauwel model

Fig. 1b:



c) Oni model

Fig. 1c:
Photoelastic models and areas of interest

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Materials and methods

The models used by Gebhardt (1911) and Pauwels (1980) do not accurately reflect the fact that the chondroepiphysis is directly continuous with the diaphyseal tube. This oversight has been corrected in this study. The model in the present study (Figure 1c) was shaped like the head of a metatarsal bone with a 2cm length of 'diaphyseal cortex' attached. The size of the model was arbitrarily chosen so that distinctive stress contours could be easily generated at relatively low loads. Two 10cm long and 10cm wide model of the cartilaginous epiphysis were made from an 8 mm thick sheet of Araldite CT 2000 with a fringe order co-efficient of 10.5×10^{-3} N/m/fringe. Model *CE or solid model* was a plain sheet designed to simulate the chondroepiphysis. Model *BE or hollow model* had a circular cut out made in its middle to simulate the bony epiphysis.

The models were mounted into a polariscope and a load of 250 Newtons was applied uniformly over the top or 'articular' end. The stress contours generated were recorded using a standard 35mm camera. The epiphysis was treated like an arch structure. Areas of interest (Figure 1c) in the haunch (A, B) and the centre (C) were defined along the transverse axis of the model. A fourth area of interest was defined in the span (D) along the vertical axis. The fringe orders in these areas were noted and the maximum shear stresses were calculated according to the stress-optic law [7] where,

$$\tau_{max} = \frac{Fn}{2t}$$

F= fringe order co-efficient, n= number of fringes and t= thickness.

Reaction fringes observed at loading points (ie keystone) and support points (ie footlings) were excluded from the analysis.

Results

Stress contours generated in *Model CE* are shown in Figure 2. There is an area of uniform low shear stresses (fringe order 0) at the centre of the model similar to that observed by Pauwels (1980). There are fringe orders of 2* at areas of interest A and B respectively and at D the fringe order is 2

Fig. 2: *Fringe patterns in photoelastic Model CE*

The stress contours generated in *Model BE* are very different as shown in Figure 3. There is an area of high stresses surrounding the cut out. A zero order is located at the centre of each haunch, A and B. At either side of A, the fringe orders are 3 and 3 respectively while at either side of B the fringe orders are 6 and 4* respectively.

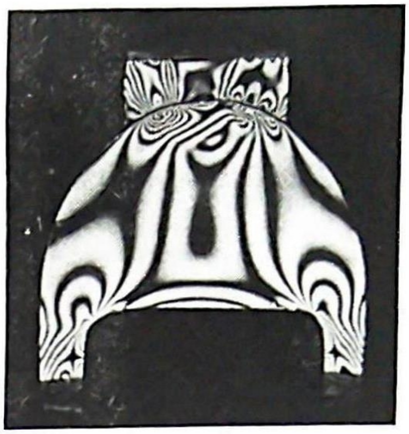

Fig. 3: *Fringe patterns in photoelastic Model BE*

The maximum shear stresses calculated following the high load experiments are shown in Table 1.

Table 1: Maximum shear stresses (N/m^{-2})

	Solid model *CE*	Fringe order no.	Hollow model *BE*	Fringe order no.
Haunch (A)	21×10^{-3}	2.5	63×10^{-3}	6
Haunch (B)	21×10^{-3}	2.5	47×10^{-3}	4.5
Centre (C)	-		-	
Span (D)	21×10^{-3}	2	21×10^{-3}	2

Discussion

Two intriguing possibilities arise from this study. First, the low stress areas at the centre of the model *CE* coincide with the centre of the cartilaginous epiphysis where the secondary centre would eventually develop as shown in the histological section in Figure 4. This would suggest that bony transformation in the cartilaginous epiphysis took place in the areas of low stresses [6]. The biological mechanism involved could be atrophy and reactive osteogenesis. According to the Wolff law [8], the areas of low stresses would atrophy as a result of disuse and they would subsequently disintegrate [9]. The necrotic cartilage can only be removed by neovascularisation since cartilage does not contain macrophages or similar scavenging cells [3]. Osteoblasts would accompany the invading blood vessels and bone would be formed as a by-product. An alternative mechanism is that proposed by Perren and Cordey (1980) [10] who demonstrated that bone formation could be induced by low strains. In this scenario, low stresses in the centre of the chondroepiphysis would cause low interstitial strains and subsequently osteoblastic transformation of the cartilage cells.

Second, the removal of material from the centre of the model *BE* is accompanied by the development of comparatively higher stresses on the inner and the outer layers of the resultant ring (Table 1). To cope with this, in the epiphysis, the inner layers would appear to be reinforced with bone and with hypertrophic cells while the outer layers are reinforced with increased cellularity (Figure 4). Furthermore, the new structure looks remarkably like an arch. The structural function of an arch is to convert axial loads into lateral ones (Figure 5). The lateral loads thus created then run round the ring of the arch and are reacted in the long bone by the diaphyseal cortical abutments. The mutual pressure generated between the elements

Fig. 4: *Photomicrograph showing a bony epiphysis*

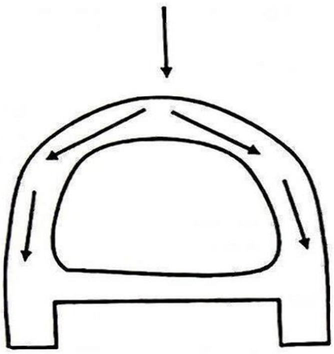

Fig. 5: *The conversion of axial into lateral loads by the bony epiphysis.*

of this arch would increase the strength of the epiphysis several hundred folds. It is presumably by these means that the long bones are able to cope with the increase in weight as the individual grows. Also, an arch is an inherently stable structure, which is not unduly sensitive to movement, distortion or to eccentric loading [11]. The span of an arch shares a proportion of the load. The span reinforces the arch and keeps the arch ends (imposts) from spreading apart. The physis is the 'span' of the epiphyseal 'arch' and it performs a mechanical function [12].

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