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Identification of material parameters of cartilage for hip joint mechanical model

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1. Introduction

Cartilage is an essential element of joint. It allows the joint surfaces to slide against one another and to distribute the pressure between them. Without cartilage, many movements would be impossible or at least painful. Understanding the mechanical behaviour of cartilage and associated parameters would allow, through appropriate modelling, to better understand the onset of certain diseases such as osteoarthritis or efficiently analyse the pressure distribution in the joint. Many studies have been conducted on the mechanical properties of cartilage. It was shown that cartilage has a viscoelastic behaviour (Juras et al. 2009; Villars et al. in press). Moreover, some studies (Kurrat and Oberländer 1978) have reported a heterogeneity of femoral head cartilage thickness, cartilage being more or less thick depending on the considered area. It would be interesting to study the heterogeneity of the viscoelastic properties of cartilage.

2. Methods

The aim of this study was to identify the viscoelastic parameters of arthrosic and non-pathological femoral head cartilage on four distinct areas using instrumented indentation testing coupled with a numerical method of identification. The experimental part of this study was to prepare samples of cartilage and then make the indentation tests. The numerical part involved modelling the indentation test by the finite element method coupled with an optimisation algorithm to minimise the error between the model response and the experience.

Samples of cartilage were dissected from femoral heads retrieved during the laying operations of total hip replacement (usually osteoarthritis heads) or intermediate hip (non-pathological head). Six non-pathological and four arthrosic femoral heads were obtained during hip replacement surgeries. The average patient age was 78 (minimum 57 years and maximum 94 years). The non-pathological femoral heads were exclusively fractures of

the femoral neck and showed no other pathology. The four studied areas (superior, inferior, posterior and anterior) were delimited by the surgeon at the end of the operation (Figure 1) and then dissected immediately.

The samples were then stored at 4°C in a solution of phosphate-buffered saline until the experimental tests did not exceed 24 h after collection. The samples had a thickness of 8 mm, a length of 25 mm and a width of 15 mm (subchondral bone and a small thickness of cancellous bone were preserved). For heads with osteoarthritis, the samples were carried out in areas where enough cartilage remained.

The tests were performed using a micro-indenter. Three consecutive measures spaced by 2 mm were performed on each area (order of measurement between areas chosen at random from one sample to the other). The tests were conducted in load–unload with a depth of 200 μm and a rate of 5 $\mu\text{m/s}$. The micro-indenter test was modelled in 2D axisymmetric with finite element software ANSYS[®]. The indenter was modelled as a rigid semi-circular arc (radius 1.5 mm). Cartilage thickness varied from 1 to 3.2 mm. The mechanical behaviour of subchondral and cancellous bones was taken into account in the model and considered as elastic isotropic. Substrate's inferior part was embedded. The contact algorithm was the augmented Lagrangian (Figure 2).

Viscoelastic parameters were identified using a Kelvin–Voigt model. Parameters were the following: E^0 is the instantaneous Young's modulus, H is the stiffness that can deduce the relaxed Young's modulus $E^\infty = (H \times E^0)/(E^0 + H)$ and η is the viscosity of the material. Identification of cartilage parameters was performed with optimisation software MIC2M (Richard 1999). From modelling of the indentation test, this software was able to write the functional (difference between model predictions and test results) to be minimised.

The optimisation problem was solved by the Levenberg–Marquardt algorithm.

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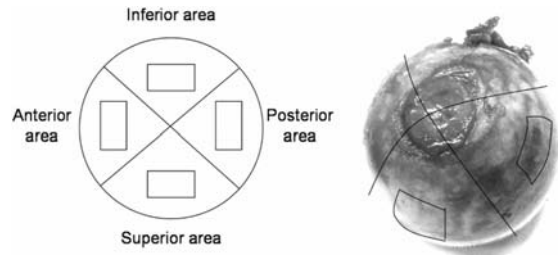


Figure 1. Area on dissected samples.

Repeatability of identifications was evaluated with the calculation of the intra-class correlation coefficient (ICC) for each parameter. This test estimated the correlation between the three identifications for each sample. Repeatability was considered as good for values of ICC higher than 75%.

The three measures performed on each area were then averaged. Viscoelastic parameters obtained on each area were compared with one another with a variance analysis (ANOVA) for each group of femoral heads (arthrosics and non-pathological heads). If $P_{ANOVA} < 0.05$, then the mean value of the parameter was different between the areas.

3. Results and discussion

A total of 29 samples were analysed (24 non-pathological and five arthrosic heads).

ICC varied from 76 to 91% for non-pathological femoral heads, whereas, for arthrosics heads, values lower than 75% were observed for E^0 , H and reached 85% for η . These results show a very good repeatability of measurements for non-pathological femoral heads. The poor repeatability observed for E^0 and H on arthrosics heads could be due to a lack of homogeneity of mechanical properties inside a given area.

Table 1. Distribution of parameters E^0 , H and η according to the measurement area for non-pathological femoral heads.

Parameter	Area	N	Mean	SD	P_{ANOVA}
E^0 (MPa)	Global	24	10.9	4.9	0.95
	Anterior	6	11.8	4.7	
	Inferior	6	10.1	5.6	
	Superior	6	11.0	5.6	
	Posterior	6	10.7	4.9	
H (MPa)	Global	24	2.2	1.5	0.76
	Anterior	6	2.4	1.2	
	Inferior	6	1.8	1.7	
	Superior	6	2.7	1.7	
	Posterior	6	2.2	1.5	
η (MPa s)	Global	24	218.7	150.4	0.75
	Anterior	6	256.2	191.1	
	Inferior	6	162.6	125.2	
	Superior	6	217.2	150.4	
	Posterior	6	238.6	153.6	

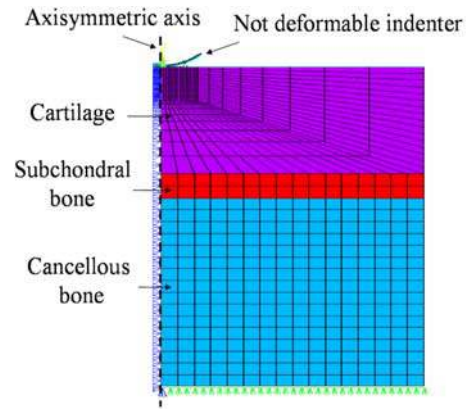


Figure 2. Finite element model of the micro-indentation test.

The parameters values obtained are also close to results found by Juras et al. (2009), values of E^0 , H and η , respectively, ranged from 2.5 to 10.7 MPa (mean, 4 MPa), 0.4 to 3.9 MPa (mean, 1 MPa) and 11.0 to 330.0 MPa s (mean, 48.4 MPa s). For non-pathological femoral heads, mean values observed for E^0 , H and η parameters were 10.9 MPa, 2.2 MPa and 218.7 MPa s, respectively. No significant difference could be put in evidence between the different areas (Table 1). For arthrosic femoral heads, mean values of parameters E^0 , H and η were 3.4 MPa, 0.6 MPa and 36.0 MPa s, respectively. No difference could be put in evidence between the different areas. Mean values of viscoelastic parameters were significantly lower for arthrosic femoral heads than for non-pathological heads.

The high values of standard deviation (SD) compared to the mean show a high dispersion of values, thus putting into evidence a high inter-individual variability. Individual analysis of each femoral head also revealed a high intra-individual variability, although no specific tendency could be detected as shown in Table 1.

This variability, added to the limited number of samples, could explain the lack of differences observed for each parameter between the four areas.

4. Conclusions

These results confirm that it is not useful to complexify models using mechanical cartilage properties. Our study showed a relative homogeneity of viscoelastic parameters within each femoral head. However, it revealed a high intra- and inter-individual variability.

Our results could be introduced in predictive calculation of hip joint (contact pressure, stress, etc.).

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