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The distribution of cartilage thickness within the joints of the lower limb of elderly individuals

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ABSTRACT

The objective of this study was to investigate the normal distribution of cartilage thickness in the major joints of the lower limb in elderly individuals. A 12.5 MHz ultrasound transducer was used to measure the cartilage thickness in the right and left hip, knee and ankle joint of 10 individuals aged between 62 and 99 y. Distribution patterns of cartilage thickness were derived by b-spline interpolation and the average distribution computed in each surface. The maximum cartilage thickness in the hip joint was 2.6 (±0.36) mm and the mean thickness 1.3 (±0.17) mm. The CV% (a measure of thickness inhomogeneity within the joint surface) was 32%. In the knee, the maximal and mean values were 3.8 (±0.46) mm and 1.9 mm (±0.24) mm, respectively (CV% = 34%), and in the ankle 1.7 (±0.25) mm and 1.0 (±0.16) mm (CV% = 32%). Systematic differences existed between both sides in the knee, the distal femur showing a significantly greater thickness on the right. While the mean and maximal thicknesses were systematically higher in the knee than in the hip, and in the hip higher than in the ankle ($P < 0.05$), there were no systematic differences in the thickness inhomogeneity of the 3 joints. Only the malleolus showed a somewhat more uniform thickness than the other joint surfaces. The variablity between individuals was similar for all joints for mean thickness, but the interindividual variability of the maximal thickness values was highest in the knee and lowest in the ankle. Whereas the cartilage thickness distributions in the joints of the lower limb have been suggested to reflect the pressure distribution within the articular surface, the absolute thickness is proposed to be a function of dynamic loading (range of motion) during gait, rather than being a reflection of the static articular pressure.

Key words: Articular cartilage; hip joint; knee joint; ankle joint; ageing; ultrasound; functional adaptation; computer models; biomechanics.

INTRODUCTION

Articular cartilage provides the bearing surfaces of synovial joints. It permits the articular surfaces to glide at extremely low friction during dynamic activity and is capable of sustaining high impact forces and of distributing these forces onto the subchondral bone. However appropriate functioning of the cartilage critically depends on the quantitative distribution of the tissue within the joint surfaces, and in particular its thickness.

It is well known that articular cartilage is distributed inhomogeneously and yields a variable thickness within the major synovial joints of the human and mammalian body (e.g. Werner, 1897; Simon, 1970). Previous anatomical studies have interpreted the thickness distribution as an expression of the long-term mechanical stress acting on the joint and have attempted to infer the loading conditions from this pattern (e.g. Kurrat & Oberländer, 1978, Eckstein et al. 1992; Milz et al. 1995, 1997). Carter and coworkers have put forward a mechanobiological theory of tissue differentiation, growth and adaptation, in which the cartilage thickness is regarded as an expression of the hydrostatic pressure acting on the articular surface (Carter, 1987, Wong & Carter, 1990). Based on idealised finite element models of synovial joints and the mathematical formulation of an ‘osteogenic

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index', they suggested that the hydrostatic pressure prevents the calcification front from progressing to the joint surface, granting that sufficient cartilage is preserved as long as the joint is loaded. This theory has been supported by animal studies in which it was shown that the cartilage thickness is diminished after joint immobilisation (Jurvelin et al. 1986) and increased after moderate training exercise (Kiviranta et al. 1987, 1994). Moreover, recent studies into the metabolic activity of chondrocytes have revealed that matrix production can be effectively enhanced by moderate dynamic loading (e.g. Sah et al. 1989; Urban, 1994; Lee & Bader, 1997), although static loading has appeared to suppress it. Apart from elucidating the structure-function relationship of the synovial joints better, quantitative data on cartilage thickness are required for constructing computer models of synovial joints (e.g. Blankevoort et al. 1991; Heegaard et al. 1995), for determining the material properties of cartilage from its deformational behaviour (Hayes et al. 1972; Lyyra et al. 1995) and for planning surgical interventions such as cartilage shaving and correction osteotomies.

The regional distribution of cartilage thickness in individual joints of the human lower limb has been reported previously (e.g. hip joint: Kurrat & Oberländer, 1978; Rushfeldt et al. 1981; Müller-Gerbl et al. 1987; knee joint: Ateshian et al. 1991; Eckstein et al. 1992; Milz et al. 1995; ankle joint: Schmitz, 1985; Müller-Gerbl & Putz, 1995). However, to our knowledge there exists no prior study in which cartilage thickness distribution in the articular surfaces has been analysed systematically in all lower limb joints in a group of individuals and in which a direct quantitative comparison has been made.

The objective of the current study was to determine the maximal and mean articular cartilage thickness as well as the regional distribution pattern in the hip, knee and ankle joint of the right and left extremities of the same individuals. As this group is becoming demographically more and more important, the joints of older subjects (without macroscopic cartilage lesions) were selected for this study.

MATERIALS AND METHODS

The right and left hip, knee, and ankle joints of 10 fixed bodies (3 male, 7 female) with an age range of 62–99 y (mean = 82.5 ± 11.7 y) were harvested from the dissection course on macroscopic anatomy and stored in 4% formalin solution. Specimens with visible surface fibrillation or other signs of joint degeneration were discarded from the study. The cadavers showed no signs of local or systemic disease of the locomotor system (Table 1).

Table 1. *Materials*

Specimen	Age (y)	Height (cm)	Sex
1	62	161	Female
2	91	160	Female
3	99	149	Female
4	83	165	Male
5	83	170	Male
6	83	156	Female
7	89	155	Female
8	72	162	Female
9	94	150	Female
10	69	172	Male

A standardised scheme of regularly distributed measuring points was marked on the surface of the acetabula (49 points), the femoral heads (84 points), the patellae (36 points), the distal femora (120 points), the tibiae (100 points), the malleoli (37 points) and the tali (127 points). The joint surfaces were then held in a water reservoir (Fig. 1) and cartilage thickness determined at each coordinate point (total = 553) with a 12.5 MHz ultrasound system (Digital Biometric Ruler, Taberna pro Medicum, Lüneburg, Germany). A plastic cap was put on the transducer to keep a constant distance of 5 mm from the joint surface (Adam et al. 1998). The cartilage thickness was measured as the distance of the 2 peaks displayed on the screen, the first one reflecting the echo at the joint surface, and the second one the interface of the uncalcified and calcified cartilage (Modest et al. 1989; Jurvelin et al. 1995).

The maximal and mean values of articular cartilage thickness were determined for each joint surface and on the right and left sides of each individual. To describe the variation of cartilage thickness within the joint surface, the coefficient of variation (CV% = standard deviation (S.D.)/mean × 100) was calculated (Ateshian et al. 1991), a CV% of zero describing a uniform distribution of cartilage (one with a constant thickness), and a high CV% an inhomogeneous distribution pattern (one with a more variable thickness).

Differences of these parameters between the right and left sides and between the opposing surfaces of each joint were tested for statistical significance at a 5% level, using the Wilcoxon test for matched pairs. The cartilage thickness of the hip, knee and ankle (opposing joint surfaces averaged) were also compared in this way, but the P value required to indicate a significant difference (5% level) was set to 0.0166, as

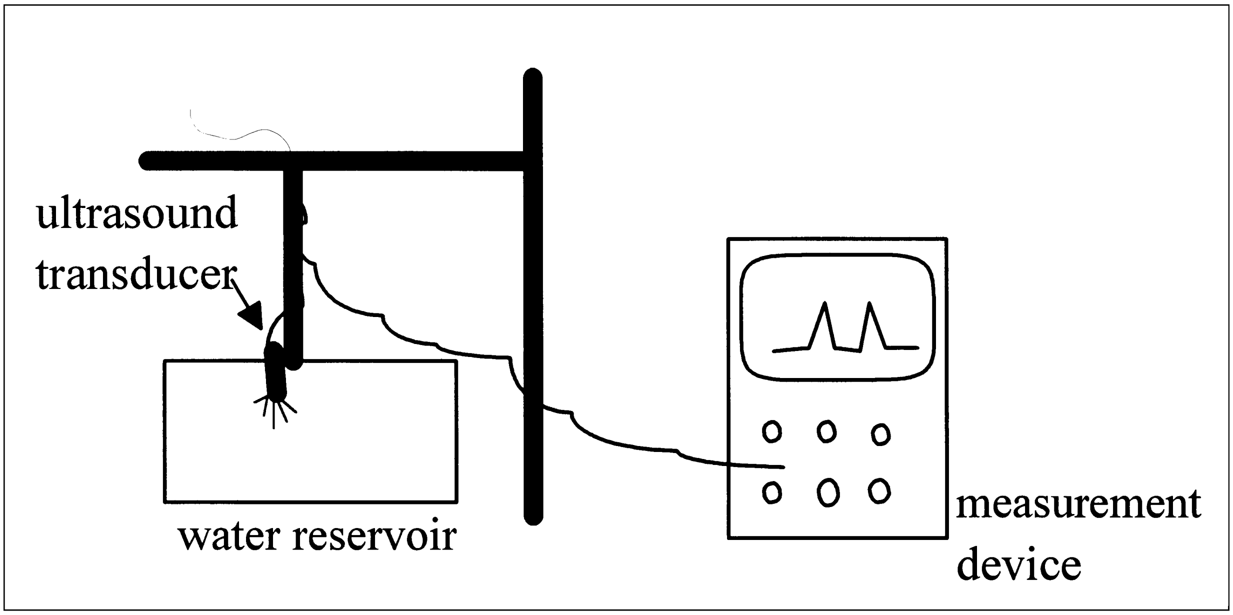

Fig. 1. A-mode ultrasound measurement of articular cartilage thickness. The joint surfaces are held in a water reservoir and cartilage thickness is measured perpendicular to the surface. The distance between the 2 peaks displayed on the screen is measured, the first demarcating the articular surface and the second the tidemark.

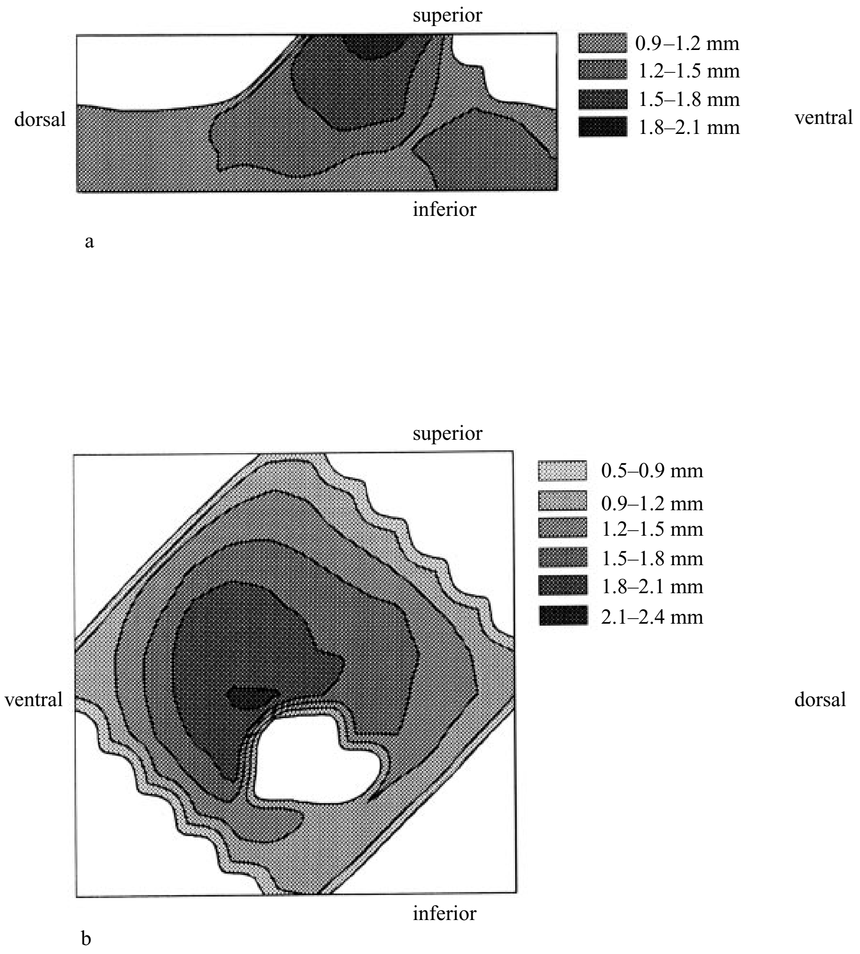

Fig. 2. Regional distribution pattern of cartilage thickness in the hip joint: (*a*) acetabulum; the maximum is located ventrally in the acetabular roof at the outer rim of the lunate surface; (*b*) femoral head; the maximum is located ventral and proximal to the insertion of the ligamentum capitis femoris.

3 pairwise tests were performed (multiple testing). Finally, all 7 joint surfaces were compared with each other (acetabulum, femoral head, distal femur, patella, tibial condyles, malleoli, talus) with the P value set to 0.0024 (21 pairwise comparisons) to confirm a significant difference at a 5 % level.

To demonstrate regional distribution patterns of cartilage thickness within the joint surfaces, Gnuplot Shareware Software was used (ftp://cmpc1.phys.soton.ac.uk; Shareware) to reconstruct cartilage thickness intervals of 0.3 mm by b-spline interpolation. Finally, average distribution patterns were obtained by demonstrating the distribution of cartilage thickness in the different joint surfaces from the average values obtained at each measuring point.

RESULTS

Hip joint

The maximal cartilage thickness (± standard deviation,) of the hip joint was 2.6 ± 0.36 mm (range = 1.7–3.1 mm), whereas the mean values amounted to 1.3 ± 0.17 mm (range = 0.9–1.5 mm) and the CV % to 32 ± 5.7 % (range = 25–43 %). The maximal thickness showed a significant negative correlation with age ($r = -0.73$; $P < 0.05$), but not the mean thickness ($r = -0.57$). There was a moderate (nonsignificant) association of the maximal ($r = 0.41$) and mean cartilage thickness ($r = 0.61$) with body height.

In the acetabulum, the cartilage thickness maximum was located ventrally in the acetabular roof at the outer rim of the lunate surface, with the thickness decreasing towards the centre. The cartilage of the femoral head was thickest ventral and proximal to the insertion area of the ligamentum capitis femoris and decreased concentrically towards the joint margins (Fig. 2). The maximal and mean cartilage thickness values and the CV % for both surfaces are shown in Figure 3. Table 2 summarises the cartilage thickness values for the right and left hip joint surfaces. No significant differences ($P < 0.05$) were observed between the right and left sides (Table 5) and no differences between the maximal cartilage thickness and the CV % of the femoral head and the acetabulum. However, the mean thickness of the femoral head was significantly greater than that of the acetabulum ($P < 0.05$).

Knee joint

The maximal cartilage thickness in the knee joint was 3.8 ± 0.46 mm (3.1–4.9 mm), the mean thickness 1.9 ± 0.24 mm (1.5–2.6 mm) and the CV % 34 ± 6.3 % (22–48 %). The maximal thickness showed a significant negative correlation with age ($r = -0.70$; $P < 0.05$), but not the mean thickness ($r = -0.31$). There was a moderate (nonsignificant) association of the maximal ($r = 0.69$) and mean thickness ($r = 0.60$) with body height.

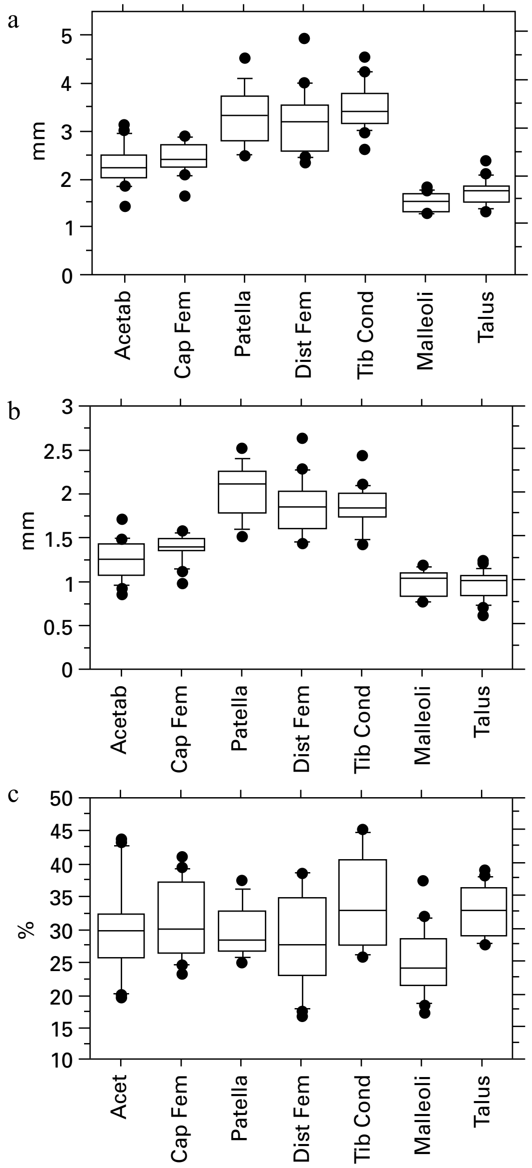

Fig. 3. Box plots showing the variation of the cartilage thickness in the various joint surfaces: (a) maximal cartilage thickness (in mm); (b) mean cartilage thickness (in mm); (c) CV % (coefficient of variaion in %), as a measure of the thickness inhomogeneity within the surface.

The maximal cartilage thickness of the patella was generally located in the middle of the lateral patellar facet. In some cases, there existed a secondary thickness maximum at the medial patellar facet and at the principle sagittal ridge (Fig. 4). At the distal femur, the maximum was situated in the middle of the femoral trochlea (facies patellaris femoris). In 6 cases, the maximal cartilage thickness of the tibia was

Table 2. *Right and left hip joint surfaces*

Joint surface	Right			Left		
	Mean (mm)±s.d. (range from/to)	Max (mm)±s.d. (range from/to)	CV %±s.d. (range from/to)	Mean (mm)±s.d. (range from/to)	Max (mm)±s.d. (range from/to)	CV %±s.d. (range from/to)
Hip (total)	1.40±0.15 (1.11/1.56)	2.73±0.30 (2.26/3.14)	32.9±6.71 (25.6/42.8)	1.30±0.17 (0.39/1.51)	2.39±0.34 (1.66/2.91)	31.0±4.91 (24.9/38.5)
Acetabulum	1.33±0.22 (1.05/1.72)	2.33±0.48 (1.85/3.14)	29.8±9.36 (20.4/44.0)	1.22±0.23 (0.85/1.49)	2.26±0.39 (1.43/2.27)	30.3±5.47 (19.8/44.0)
Femoral head	1.43±0.15 (1.12/1.59)	2.57±0.27 (2.16/2.89)	33.2±6.56 (24.9/41.2)	1.35±0.16 (0.99/1.52)	2.34±0.35 (1.66/2.91)	29.8±5.22 (23.3/38.3)

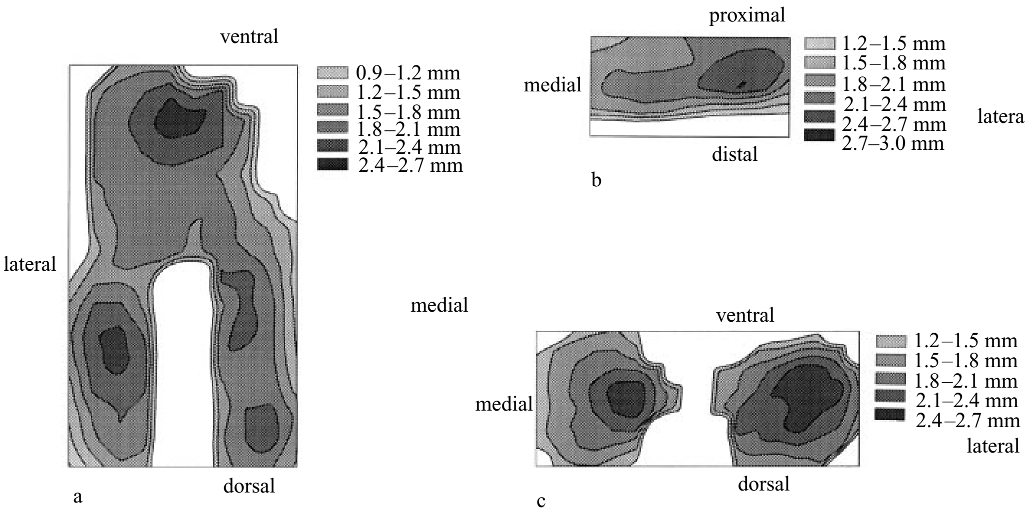

Fig. 4. Regional distribution pattern of cartilage thickness in the knee joint: (a) distal femur; the maximum is located in the middle of the femoral trochlea; (b) patella; the maximum is located in the middle of the lateral patellar facet; (c) tibial plateau; the maximum is located in 6 cases in the centre of the medial and in 12 cases in the centre of the lateral plateau.

Table 3. *Right and left knee joint surfaces*

Joint surface	Right			Left		
	Mean (mm)±s.d. (range from/to)	Max (mm)±s.d. (range from/to)	CV %±s.d. (range from/to)	Mean (mm)±s.d. (range from/to)	Max (mm)±s.d. (range from/to)	CV %±s.d. (range from/to)
Knee (total)	1.95±0.27 (1.57/2.55)	3.86±0.59 (3.08/4.91)	32.8±5.85 (22.1/41.4)	1.81±0.20 (1.51/2.17)	3.65±0.27 (3.32/4.06)	34.7±6.88 (26.0/47.7)
Patella	2.07±0.37 (1.51/2.52)	3.43±0.76 (2.52/4.52)	30.8±4.64 (26.4/37.5)	2.01±0.26 (1.63/2.28)	3.25±0.49 (2.49/3.82)	28.9±3.77 (25.1/35.8)
Femur	1.92±0.33 (1.54/2.64)	3.18±0.70 (2.32/4.91)	27.0±7.02 (16.7/36.6)	1.77±0.30 (1.43/2.29)	3.10±0.66 (2.32/4.00)	31.9±11.39 (20.5/54.4)
Tibia	1.91±0.28 (1.42/2.43)	3.52±0.54 (2.92/4.52)	30.9±11.3 (6.6/45.2)	1.80±0.20 (1.41/2.02)	3.42±0.44 (2.59/4.06)	35.5±6.46 (26.8/45.2)

located in the centre of the medial and in 12 cases in the centre of the lateral plateau (Fig. 4).

Figure 3 shows the maximal and mean cartilage thickness and the CV % for all 3 articular surfaces, and Table 3 lists these values separately for the left and right sides. The mean cartilage thickness values in the knee (all joint surfaces averaged) were higher on the right than on the left side ($P < 0.05$). The same applied when comparing the right and left distal femur, but not when analysing the right and left

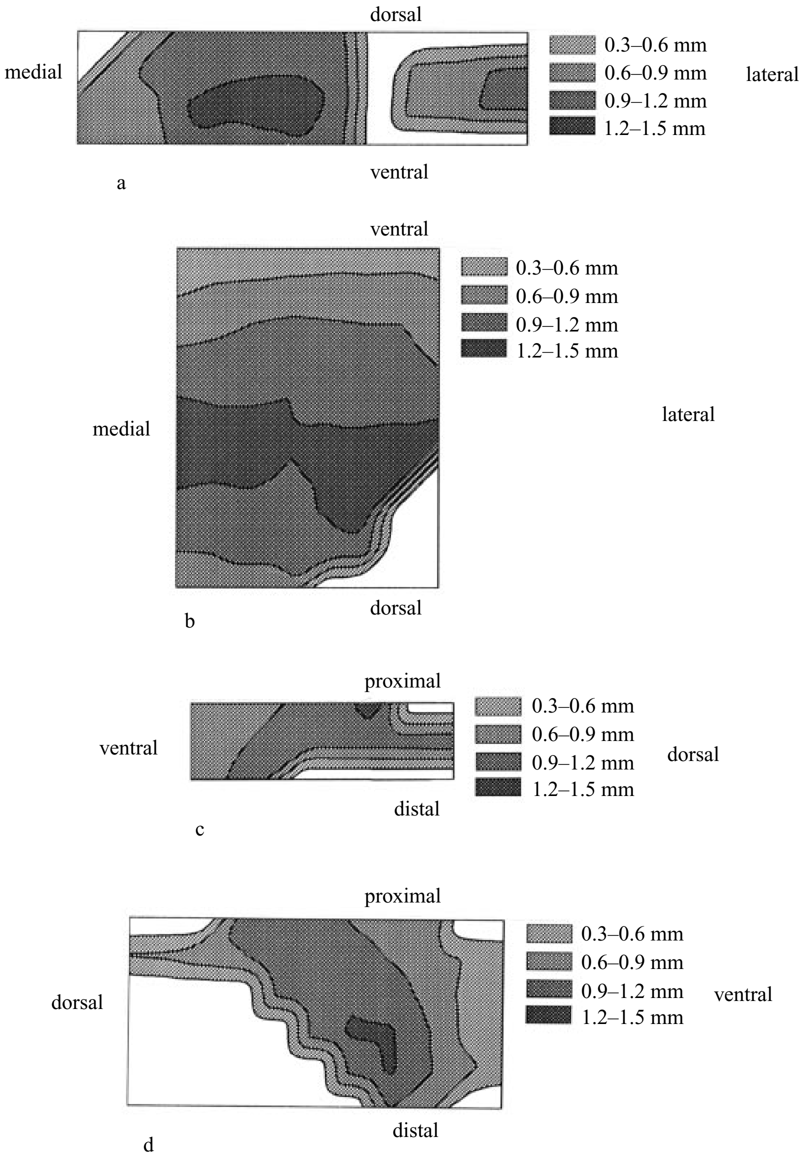

Fig. 5. Regional distribution pattern of cartilage tickness in the ankle joint: (a) malleoli; the maximum is located in the middle of the tibia; (b) superior talar facet; (c) medial talar facet; (d) lateral talar facet; the maximum is located in a plateau-like area between the middle and dorsal thirds of the superior facet.

patella and the tibia (Table 5). No significant side differences between the maximal thickness values of any of these surfaces or the CV% were recorded (Table 5). Also, no significant differences between maximal and mean cartilage thickness and CV% could be detected between the patella, the femur and the tibia.

Ankle joint

The maximal cartilage thickness of the ankle joint was 1.7 ± 0.25 mm (1.3–2.3 mm), the mean thickness 1.0 ± 0.16 mm (0.7–1.2 mm) and the CV% 32 ± 4.0% (26–39%). Neither the maximal nor the mean thickness showed a significant negative correlation with age ($r = -0.14$; $r = -0.45$). There was a moderate (nonsignificant) association of the maximal ($r = 0.40$) and mean thickness ($r = 0.54$) with body height.

The maximal thickness in the malleoli was located in the middle of the tibial part of the joint surface, with a regular secondary maximum at the edge of the lateral malleolus (Fig. 5). The distribution pattern of cartilage thickness in the talus showed the thickest cartilage in a plateau-like area between the middle and dorsal third of the superior facet (Fig. 5). This maximum extended to the superior part of the medial facet. The lateral facet yielded a second, independent maximum in its centre.

Table 4. *Right and left ankle joint surfaces*

Joint surface	Right			Left		
	Mean (mm) ± S.D. (range from/to)	Max (mm) ± S.D. (range from/to)	CV % ± S.D. (range from/to)	Mean (mm) ± S.D. (range from/to)	Max (mm) ± S.D. (range from/to)	CV % ± S.D. (range from/to)
Ankle joint	0.97 ± 0.17	1.74 ± 0.19	31.3 ± 4.26	0.94 ± 0.16	1.67 ± 0.29	31.8 ± 3.85
(total)	(0.71/1.18)	(1.42/2.08)	(26.0/37.7)	(0.65/1.22)	(1.33/2.31)	(28.0/39.0)
Malleoli	1.00 ± 0.17	1.50 ± 0.19	25.3 ± 6.12	0.97 ± 0.12	1.46 ± 0.20	24.9 ± 4.81
	(0.75/1.19)	(1.23/1.72)	(19.2/37.4)	(0.79/1.16)	(1.24/1.80)	(17.8/32.3)
Talus	0.96 ± 0.16	1.73 ± 0.21	32.4 ± 3.87	0.93 ± 0.17	1.63 ± 0.32	33.3 ± 4.02
	(0.70/1.18)	(1.42/2.08)	(27.6/37.7)	(0.60/1.23)	(1.25/2.31)	(28.5/38.9)

Table 5. *Statistical comparison left vs right*

	P value		
	mean left vs right	Max left vs right	CV % left vs right
Hip (total)	0.2626	0.1614	0.4838
Acetabulum	0.4008	0.5754	0.5754
Femoral head	0.3270	0.4008	0.3270
Knee (total)	0.0117 ($r > 1$)	0.2361	0.1097
Patella	0.5002	0.4631	0.1730
Femur	0.0180 ($r > 1$)	0.4008	0.0687
Tibia	0.1097	0.3433	0.3743
Ankle joint (total)	0.4838	0.4838	0.8785
Malleoli	0.7263	0.5754	0.8886
Talus	0.1731	0.2026	0.4446

Table 6. *Statistical comparison of the maximal cartilage thicknesses of the joint surfaces of the lower limb with each other*

(*a*)

	Knee joint	Ankle joint
Hip joint	0.0004 ($k > h$)*	0.0005 ($h > a$)*
Knee joint	—	0.0002 ($k > a$)*

* Significant at 5% level; $P < 0.017$.

(*b*)

	Femoral head	Patella	Distal femur	Tibial plateau	Malleoli	Talus
Acetabulum	0.1359	0.0096	0.0023 ($f > a$)*	0.0005 ($t > a$)*	0.0004 ($a > m$)*	0.0004 ($a > ta$)*
Femoral head	—	0.0037	0.0061	0.0003 ($t > fh$)*	0.0003 ($fh > m$)*	0.0003 ($fh > ta$)*
Patella	—	—	0.2094	0.8753	0.0042 ($p > m$)*	0.0022 ($p > ta$)*
Distal femur	—	—	—	0.1556	0.0004 ($f > m$)*	0.0004 ($f > ta$)*
Tibial plateau	—	—	—	—	0.0002 ($t > m$)*	0.0002 ($t > ta$)*
Malleoli	—	—	—	—	—	0.0039

* Significant at 5% level; $P < 0.0024$.

Table 4 summarises these values for the left and right sides of the ankle joint surfaces. No significant differences of the mean and maximal cartilage thickness and the CV% were observed between the right and left joints (Table 5). The maximal cartilage thickness and the CV% of the talus were significantly greater than that of the malleoli ($P < 0.05$), while the mean cartilage thickness did not differ significantly (Table 7).

Comparison between the joints of the lower limb

In a first step, we compared the cartilage thickness in the hip, knee and ankle, after averaging the surfaces

Table 7. *Statistical comparison of the mean cartilage thicknesses of the joint surfaces of the lower limb with each other*

(*a*)

	Knee joint	Ankle joint
Hip joint	0.0003 ($k > h$)*	0.0004 ($h > a$)*
Knee joint	—	0.0002 ($k > a$)*

* Significant at 5% level; $P < 0.017$.

(*b*)

	Femoral head	Patella	Distal femur	Tibial plateau	Malleoli	Talus
Acetabulum	0.0151	0.0022 ($p > a$)*	0.0007 ($f > a$)*	0.0003 ($t > a$)*	0.0012 ($a > m$)*	0.0005 ($a > ta$)*
Femoral head	—	0.0022 ($p > fh$)*	0.0008 ($f > fh$)*	0.0005 ($t > fh$)*	0.0004 ($fh > m$)*	0.0003 ($fh > ta$)*
Patella	—	—	0.1467	0.0597	0.0022 ($p > m$)*	0.0022 ($p > ta$)*
Distal femur	—	—	—	0.8203	0.0004 ($f > m$)*	0.0004 ($f > ta$)*
Tibial plateau	—	—	—	—	0.0002 ($t > m$)*	0.0002 ($t > ta$)*
Malleoli	—	—	—	—	—	0.4925

* Significant at 5% level; $P < 0.0024$.

Table 8. *Statistical comparison of the CV% values of the joint surfaces of the lower limb with each other*

(*a*)

	Knee joint	Ankle joint
Hip joint	0.6192	0.9434
Knee joint	—	0.2145

* Significant at 5% level; $P < 0.017$.

(*b*)

	Femoral head	Patella	Distal femur	Tibial plateau	Malleoli	Talus
Acetabulum	0.7226	0.7537	0.4691	0.3560	0.0552	0.1128
Femoral head	—	0.0995	0.3794	0.3318	0.0004 ($fh > m$)*	0.3560
Patella	—	—	0.3078	0.2393	0.1169	0.0597
Distal femur	—	—	—	0.1961	0.0980	0.1627
Tibial plateau	—	—	—	—	0.0084	0.7771
Malleoli	—	—	—	—	—	0.0005 ($t > m$)*

* Significant at 5% level; $P < 0.0024$.

within each joint. While the mean and maximal thickness were significantly higher in the knee than in the hip, and higher in the hip than in the ankle (Tables 6*a*, 7*a*; $P < 0.017$), there was no significant difference in the thickness inhomogeneity (CV%) (Table 8*a*).

Comparing all 7 joint surfaces (acetabulum, femoral head, distal femur, patella, tibial condyles, malleoli, talus) with each other (Fig. 3), we found the maximal thickness of the distal femur and tibia, and the mean thickness of the patella, distal femur and tibial plateau to be significantly higher than those of the acetabulum and femoral head ($P < 0.0024$). The mean and maximal thickness of the malleolus and talus were, in contrast, significantly lower than those of the acetabulum and the femoral head (Tables 6*b*, 7*b*). The cartilage thickness inhomogeneity of the femoral head and the talus was significantly higher than that of the malleolus (Table 8*b*).

Analysing the variability of cartilage thickness between individuals (S.D./mean values of the group), no striking differences between the various joint surfaces of the lower limb were noted with regard to the mean cartilage thickness (actabulum = 17%, femoral head = 11%, patella = 15%, distal femur = 17%, tibial condyles = 13%, malleoli = 14%, talus = 17%). However, the maximal cartilage thickness values in the knee appeared to show a higher variability between individuals (patella = 37 %, distal femur = 49 %, tibial condyles = 23 %) than those of the hip (actabulum = 18 %, femoral head = 11 %), and those of the hip a higher one than those of the ankle joint (malleoli = 4 %, talus = 7 %) (Fig. 3*a*).

DISCUSSION

In the current study we have determined the normal distribution of articular cartilage thickness in the major joints of the lower limb in elderly individuals with A-mode ultrasound. We find that, despite considerable interindividual differences, there exists a similar degree of thickness inhomogeneity in all articular surfaces, with only the malleolus showing a somewhat more uniform distribution. Systematic differences between the mean cartilage thickness at the left and right side existed only in the knee, with the right distal femur yielding a significantly greater thickness. The cartilage was found to be thicker in the knee than in the hip, and thicker in the hip than in the ankle joint. The interindividual variability of the mean cartilage thickness was similar in the joint surfaces of the lower limb of elderly individuals, whereas that of the maximal values was highest in the knee and lowest in the ankle.

Methodology

For determining the typical distribution pattern of cartilage thickness throughout entire joint surfaces, a high number of measuring points is required. Because of its high time and cost effectiveness, and because the cartilage can be measured perpendicular to all aspects of the joint surfaces, an ultrasonic technique was selected. Previously, A-scan ultrasound has been shown to measure articular cartilage thickness accurately (Modest et al. 1989; Jurvelin et al. 1995), the first echo being reflected at the joint surface and the second at the tidemark (the interface between the calcified and uncalcified cartilage layer zone of the joint cartilage). In an earlier study, we have shown that the measurement system used in the current investigation yields accurate values in comparison with MR, CT arthrography and anatomical sections (Eckstein et al. 1997*a*; Adam et al. 1998), that the measurements are highly reproducible, and that formalin fixation has no measurable effect on the mean and maximal cartilage thickness as well as the CV % as a measure of cartilage thickness inhomogeneity (Adam et al. 1998). The latter finding is consistent with the results of Kurrat (1977) and Fischer (1988), and we therefore assume that the thickness values described here correspond closely to the in vivo situation in normal joints of older individuals.

Comparison between the cartilage thickness distribution in the hip, knee and ankle with the loading conditions in these joints

Hip joint. The absolute thickness values and the relative distribution patterns of the hip joint cartilage thickness in our study are in good agreement with the description given by Kurrat & Oberländer (1978), Rushfeldt et al. (1981) and Müller-Gerbl et al. (1987). Kurrat & Oberländer (1978) found somewhat higher maximal values, but this may be attributed to the fact that their study included younger subjects than ours (ages 34–86 y). Armstrong & Gardner (1977) examined 28 right femoral heads (ages 10–68 y) with conventional radiography and Hodler et al. (1992) 10 hip joint specimens with MR imaging (ages 62–81 y). Their values are also in the range of those found in our study, but these authors did not report the distribution of cartilage within the joint surfaces.

Comparing the distribution of cartilage thickness with the long-term loading conditions in the joint, the ventral localisation of the maximal cartilage thickness in the hip corresponds with a ventral orientation of the joint reaction force as measured in vivo during normal walking and running (Bergmann et al. 1993) with telemetric hip endoprostheses; and also with a pressure maximum observed in the ventral aspect of the acetabular roof during a simulated stance phase (von Eisenhart-Rothe et al. 1997; Widmer et al. 1997).

Knee joint. The relative distribution pattern of cartilage thickness in the knee is also in agreement with that reported by previous authors (Ateshian et al. 1991; Eckstein et al. 1992; Milz et al. 1995), but whereas the absolute cartilage thickness in the present study is similar to that reported by the authors who examined older specimens (Eckstein et al. 1992; Milz et al. 1995), it is considerably lower than that in younger specimens (Ateshian et al. 1991). Meachim et al. (1977) reported that the cartilage thickness of the patella decreases significantly with age, particularly in women above 50 y. They attributed this to an increasing prevalence of osteoarthrosis, but the present finding suggests that the cartilage thickness in the knee decreases with age, independent of cartilage lesions.

Comparing the cartilage thickness with the loads acting on the knee joint, the bicentric thickness distribution in the patella (maxima in the lateral facet and at the medial ridge) fits in well with the description of the joint pressure distribution by Huberti & Hayes (1984) and Hehne (1990). These authors have reported that the load bearing areas of the patella and facies patellaris femoris divert into 2 separate parts on the lateral and medial patellar facets at deep knee bending. However, the lateral patellar facet is weight-bearing during all flexion angles (Hehne 1990), and this may explain why the absolute maximum is generally located in this facet. In the femorotibial joint, high contact pressures have been reported to act in the central parts (Ahmed & Burke 1983, *a*, *b*), again at the sites where we find the cartilage maxima. In the tibial joint surface, the thickness distribution of the cartilage is also very similar to that of the thickness of the subchondral bone (Milz & Putz, 1994), a parameter which has also been suggested to reflect the long-term distribution of joint stress. However, in the patella it has been shown that neither the subchondral bone density (Eckstein et al. 1992) nor subchondral thickness (Milz et al. 1995) show a highly positive correlation with the thickness of the uncalcified cartilage. Bruns et al. (1993) observed in a biomechanical experiment that the contact pressures are usually higher in the medial than in the lateral tibial plateau. We found the medial cartilage thickness to be higher in 6, but to be lower in 12 cases.

Ankle joint. The distribution of cartilage thickness in the ankle has been previously investigated by Schmitz (1985) in 23 tali (ages 59–86 y), and by Müller-Gerbl & Putz (1995), who examined 8 tali of unknown age. Whereas Schmitz (1985) reported a maximal cartilage thickness of about 1.3 mm (thus corresponding closely with our findings), Müller-Gerbl & Putz observed values of up to 3 mm. However, the relative distribution patterns of cartilage thickness of both studies are very similar to our results.

Biomechanical investigations of the ankle-joint with Fuji Prescale film (Bruns & Rosenbach, 1990) have shown that in the normal position of the joint the highest contact stresses occur in the middle of the superior facet of the talus and the distal tibia, at the location where we find the maxima of cartilage thickness.

Comparison of cartilage thickness in the joint surfaces of the lower limb

The finding that the mean and maximal cartilage thickness are significantly greater in the human knee than in the hip, and greater in the hip than in the ankle, is in agreement with the observations made by Simon (1970) who made the same observation in other mammals, such as the cow, sheep, dog and rat. Only in the mouse was the cartilage thickness in the hip greater than in the knee. Despite differences between the mean and maximal cartilage thickness values in these joints, the thickness inhomogeneity is relatively similar in all surfaces (CV% ~ 30%), with only the malleolus showing a somewhat more uniform distribution.

The question arises why differences between the mean and maximal cartilage thickness of the joints of the lower limb occur. One possible explanation is the different size of the joints, the articular surfaces of the knee being greater than those of the hip, and those of the hip greater than those of the ankle. However, this can only explain differences between the cartilage thickness in the entire joints, and not those between the various joint surfaces. The patella, for instance, is considerably smaller than the femoral head, but yields a much higher thickness.

Simon (1970) studied the correlation between cartilage thickness and the static compressive stress in the joints of various quadrupeds, calculating the joint reaction force in a relaxed standing position and determining the size of the joint contact area in a compression experiment. He found no systematic relationship between these variables, but did not exclude the possibility that there may be relationship with the stresses encountered during dynamic activity. Although quantitative in vitro data on the static pressure in the joints of the lower human limb are available, these are difficult to compare systematically, as different loading conditions were applied. Based on the suggestions of Braune & Fischer (1891) who assumed a direct correlation between cartilage thickness and joint congruity, Simon et al. (1973) compared the congruence (defined as the length of contact in a section through a joint in experimental compression, divided by the maximal possible length of contact) in various canine joints. They reported an almost linear inverse relationship, the highest incongruity and lowest cartilage thickness being observed in the ankle, and the lowest congruity and highest cartilage thickness in the knee (menisci excluded from the analysis). Data on joint incongruity have been reported in some joints of the human lower limb (e.g. Riede et al. 1971; Eckstein et al. 1997*b*), but these are difficult to compare in quantitative terms. However, we believe that joint congruence does not provide a satisfactory explanation of variations in cartilage thickness, as the human humero-ulnar articulation shows a very high degree of incongruity (Eckstein et al. 1993, 1995), but yields a relatively thin cartilage (Milz et al. 1997).

From kinematic analyses (Braune & Fischer, 1995), however, it is evident that the range of motion for normal walking and running is highest at the knee, followed by the hip and eventually by the ankle. It is thus possible that the thickness of the cartilage may be determined by the degree of dynamic loading of the joints of the lower limb during normal activity. This idea is supported by animal studies that have shown that moderate dynamic loading increases cartilage thickness, and by biomechanical studies in cartilage explants, showing that dynamic loading enhances chondrocyte biosynthesis (Sah et al. 1989; Urban, 1994; Lee & Bader, 1997). It is interesting to note that the prevalence of osteoarthrotic degeneration is positively related to the cartilage thickness in the joints of the lower limb (Heine, 1926). It is, however, unclear whether this phenomenon is directly related to the cartilage thickness, or whether the thickness must be regarded as a result of functional adaptation to mechanical stimuli, which, after adaptation has come to a physiological limit, may also cause tissue failure.

CONCLUSION

We find that the maximal and mean cartilage thickness in the human knee is higher than that of the hip, and that of the hip higher than that of the ankle. Apart from the malleoli, all joint surfaces of the lower limb yield a similar average degree of thickness inhomogeneity. The interindividual variability of mean cartilage thickness appears to be similar in the major joint surfaces of the lower limb of elderly individuals, whereas that of the maximal values was highest in the knee and lowest in the ankle. The thickness distribution within the joint surfaces is suggested to reflect the pressure distribution within the joint surface of in vitro loading experiments, but the absolute thickness is proposed to be a function of dynamic loading (range of motion) during gait, rather than a reflection of the static pressure.

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