Thickness of the subchondral mineralised tissue zone (SMZ) in normal male and female and pathological human patellae

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ABSTRACT

The objective of this paper was to analyse sex differences of the thickness of the subchondral mineralised tissue zone (SMZ), and to find out whether systematic changes of SMZ thickness are associated with naturally occurring, non-full-thickness cartilage lesions of human patellae. In 32 methyl-methacrylate-embedded specimens (16 normal, 8 with focal medial, and 8 with lateral lesions) the SMZ thickness was determined, using a binocular macroscope and an image analysing system. In each case, the thickness distribution was reconstructed throughout the entire joint surface. The maximal and mean SMZ thicknesses were significantly higher in males than in females ($P < 0.01$). In normal patellae and those with lateral lesions, the thickness was significantly thicker laterally than medially ($P < 0.05$), but it was not in specimens with medial damage. Patellae with medial damage exhibited a significantly lower total mean and lateral mean ($P < 0.05$). A lower SMZ thickness was found directly beneath medial lesions than beneath lateral ones, but the local thickness was always in the range of that observed in normal specimens. We conclude that differences of patellar SMZ thickness exist between males and females. Naturally occurring cartilage lesions appear, however, not to be associated with local changes of SMZ thickness, but they may be associated with an altered regional distribution pattern within the joint surface.

Key words: Subchondral bone; cartilage lesions; femoropatellar joint; chondromalacia patellae.

INTRODUCTION

Articular cartilage and subchondral bone act in concert in transmitting loads through joints, and the integrity of both tissues is required for appropriate functioning. The linkage of the hyaline cartilage and the subchondral bone is provided by a thin layer of calcified cartilage (Redler et al. 1975; Milz & Putz, 1994) which, together with the subchondral bone layer, may be called the subchondral mineralised tissue zone (SMZ, Fig. 1). This zone may be regarded as a morphological and mechanical unit and has been recognised to play an important role in attenuating the axial impact forces typically encountered during dynamic joint loading (Radin & Paul, 1970; Radin et al. 1970; Hoshino & Wallace, 1978; Radin & Rose, 1986).

It has been suggested that (1) subchondral bone adapts to the mechanical demands made upon it during normal and abnormal joint function, thus reflecting the long-term distribution of stress in the joint surfaces (Pauwels, 1963, 1980; Tillmann & Brade, 1980; Müller-Gerbl et al. 1989, 1994) and that (2) subchondral bone plays an important role in the
pathogenesis of cartilage degeneration. A thickening of the SMZ has been suggested to increase the internal cartilage stresses by either bringing about a higher stiffness of the subchondral bone or by progressive thinning of the cartilage layer (Radin et al. 1970, 1972, 1978, 1991; Simon & Radin, 1972; Brown et al. 1984; Wu et al. 1990; Shimizu et al. 1993).

Whereas numerous investigations have previously dealt with the radiological density of the subchondral bone in man under physiological and pathological conditions (Pauwels, 1963, 1980; Tillmann & Brade, 1980, Müller-Gerbl et al. 1989, 1994; Eckstein et al. 1992, 1993, 1995), only a few have focused on its actual thickness. Studies on the relationship of cartilage damage and the thickness of the underlying subchondral bone have so far yielded contradictory results. Both an increased and decreased SMZ thickness have been reported in animal models of osteoarthrosis (Simon & Radin, 1972; Benske et al. 1988; Layton et al. 1988; Dedrick et al. 1991, 1993, 1995; Armstrong et al. 1994) and in human joints (Darracott & Vernon-Roberts, 1971; Christensen et al. 1982; Chai et al. 1991; Grynpas et al. 1991; Shimizu et al. 1993). However, in these studies the SMZ thickness was usually measured at certain (defined) points, but not systematically throughout the entire joint surface.

Only recently has the regional distribution of SMZ thickness been reported in human tibiae (Milz & Putz, 1994) as well as in normal patellae and proximal ulnae (Milz et al. 1995, 1997), in which a relatively low correlation with the thickness of the uncalcified cartilage was demonstrated. However, it is open to question whether there exist systematic differences between males and females in general and/or whether the local distribution of SMZ thickness is altered in the case of naturally occurring cartilage lesions. Being the place of earliest and most severe cartilage damage in the body (Ficat & Hungerford, 1977) and showing more progressive cartilage damage at its lateral than at its medial facet (Meachim & Emery, 1974), the patella is ideally suited for such an analysis, and it has even been termed an ‘ideal observatory’ for cartilage degeneration (Ficat, 1973).

The objective of the current study was therefore to examine the topographical thickness distribution of the subchondral mineralised tissue zone (SMZ) in male and female human patellae, and in specimens with naturally occurring, focal, non-full-thickness cartilage lesions.

The specific questions to be addressed were: (1) Are there systematic differences in SMZ thickness between normal men and women? (2) Do specimens with different sites of focal cartilage lesions (medial or lateral) yield different distribution patterns of SMZ thickness throughout the joint, possibly indicating an alteration of the long-term mechanical loading responsible for these lesions? (3) Are focal, non-full-thickness cartilage lesions associated with locally increased or decreased SMZ thickness at these specific locations?

**MATERIALS AND METHODS**

32 cadaveric human patellae (aged 54–92 y, mean 78 y; 14 males, 18 females), fixed in a solution of 4% formalin, were chosen from about 200 dissecting-room subjects which consisted of 45% males and 55% females. The criteria by which they were selected were the absence of macroscopically visible cartilage damage or the presence of a circumscribed, focal non-full-thickness cartilage lesion, either in the medial or lateral patellar facet. In 16 specimens (8 male, 8 female) the cartilage was intact and showed no sign of damage on naked eye inspection; 16 cadavers exhibited focal cartilage lesions grade 2 or 3 (classification of Outerbridge, 1961), the damage being located in 8 cases in the medial, and in 8 in the lateral facet of the patella. The lesions had a diameter between 0.2 and 2 cm and comprised 1–2-thirds of the thickness of the cartilage layer; specimens with generalised cartilage damage or exposure of the bone–cartilage interface were discarded from the study. No data were available about the past medical and social history of the individuals from whom the specimens were obtained.

The patellae were dehydrated and embedded in methylmethacrylate (Milz & Putz, 1994; Milz et al. 1995). The ventral part of the specimens was cut open to accelerate the embedding process. Because the articular surface of the patella is mainly curved within the transverse plane, transverse 500 µm sections were obtained at intervals of 3400 µm with a saw microtome (Leitz, Wetzlar, Germany), in order to keep angular distortion of the thickness measurements minimal. Figure 2a shows a contact radiograph of a section from a patella without a cartilage lesion. Additional sections, 100 µm thick, were stained with van Gieson (Fig. 2b). The thickness of the SMZ was assessed from the 500 µm transverse sections at intervals of 4 mm from the main patellar ridge to the periphery on either side, and additional measurements were made directly beneath the lesions. The distances from the tidemark (the border between the uncalcified and the calcified cartilage) to the transitional line of the SMZ and the subarticular trabecular bone were
measured perpendicular to the bone–cartilage interface at a magnification of ×15 (Fig. 3), using a Wild M 420 binocular macroscope (Wild Leitz, Heerbrugg, Switzerland—numerical aperture 0.25) in connection with an IPS 10 image analysing system (Kontron, Eching, Germany). In a previous study (Milz & Putz, 1994), the precision of the thickness measurements was confirmed to be in the range of 5–10 µm. To obtain a comprehensive visual display, topographical thickness maps were prepared from the measuring points by Gnuplot software (Computer Solutions, Grafing, Germany), with b-spline interpolation and isolines delineating thickness intervals of 100 µm (Fig. 4).
The following parameters were evaluated: (1) the maximal thickness of the SMZ, (2) the position of the maximum and the distribution pattern of SMZ thickness, (3) the total mean thickness of the SMZ (all measuring points), (4) the mean SMZ thickness of the medial and lateral patellar facets, and (5) the local thickness of the SMZ beneath focal (medial or lateral) cartilage lesions. The mean values of the medial and lateral facets were compared statistically using the Wilcoxon test for matched pairs; differences between males and females and between specimens with and without lesions were evaluated with the Mann–Whitney U test.

RESULTS

SMZ thickness in normal male and female specimens

The SMZ was found to exhibit a high degree of variation of thickness within each patella, and there were also important differences between individual specimens. In normal male patellae (Table 1) the maximal thickness varied between 1000 µm and 2110 µm (mean = 1530 ± 380 µm) and in females (Table 2) between 770 and 1390 µm (mean = 1070 ± 260 µm). With the exception of 1 specimen, the maxima were always localised in the lateral patellar facet. From this maximum, the SMZ thickness generally decreased to values of less than 100 µm at the patellar margin (Fig. 4). In some cases, a secondary maximum was observed between the paramedian segment and the odd facet, just beneath the medial patellar ridge (Fig. 4a). The distribution pattern did not show systematic variations between males and females. The total mean of SMZ thickness ranged from 430 to 730 µm (mean = 620 ± 120 µm) in normal male specimens (Table 1) and from 350 to 570 µm (mean = 440 ± 70 µm) in the females (Table 2). In both sexes the mean lateral thickness was significantly greater than that of the medial facet (P < 0.05). In the male group the maximal thickness (P < 0.01), the total mean (P < 0.01), the lateral mean (P < 0.01) and also the medial mean SMZ thickness (P < 0.05) were greater than in females (Fig. 7). Within the male group and within the female group no significant correlation between these parameters and either the age or the body size was found.

Table 1. Thickness of the subchondral mineralised tissue zone (SMZ) in normal male patellae

<table>
<thead>
<tr>
<th>Age (y)</th>
<th>Body size (cm)</th>
<th>Maximum and location of the SMZ thickness (µm)</th>
<th>Mean of the total patella (µm)</th>
<th>Mean of the medial facet (µm)</th>
<th>Mean of the lateral facet (µm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>540</td>
<td>730</td>
</tr>
<tr>
<td>64</td>
<td>166</td>
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<td>430</td>
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<td>480</td>
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<td>68</td>
<td>170</td>
<td>2110 LF</td>
<td>770</td>
<td>630</td>
<td>890</td>
</tr>
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<td>1350 LF</td>
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<td>460</td>
<td>650</td>
</tr>
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<td>74</td>
<td>167</td>
<td>1510 LF</td>
<td>730</td>
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<td>800</td>
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<tr>
<td>82</td>
<td>185</td>
<td>2100 LF</td>
<td>750</td>
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<td>880</td>
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<td>610</td>
<td>590</td>
<td>680</td>
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</table>

LF, lateral facet; MF, medial facet; PR, principal ridge; minima and maxima are marked bold.

Table 2. Thickness of the subchondral mineralised tissue zone (SMZ) in normal female patellae

<table>
<thead>
<tr>
<th>Age (y)</th>
<th>Body size (cm)</th>
<th>Maximum and location of the SMZ thickness (µm)</th>
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<th>Mean of the medial facet (µm)</th>
<th>Mean of the lateral facet (µm)</th>
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<td>76</td>
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<td>470</td>
<td>650</td>
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<tr>
<td>76</td>
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<td>83</td>
<td>153</td>
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<td>89</td>
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<td>770 LF</td>
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<tr>
<td>91</td>
<td>145</td>
<td>1330 LF</td>
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<td>280</td>
<td>410</td>
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</tbody>
</table>

LF, lateral facet; MF, medial facet; PR, principal ridge; minima and maxima are marked bold.
Table 3. Thickness of the SMZ in patellae with cartilage lesions at the medial facet

<table>
<thead>
<tr>
<th>Age (y)</th>
<th>Body size (cm)</th>
<th>Maximum and location of the SMZ thickness (µm)</th>
<th>Mean of the total patella (µm)</th>
<th>Mean of the medial facet (µm)</th>
<th>Mean of the lateral facet (µm)</th>
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<td>810 MF</td>
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</tr>
<tr>
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<td>350</td>
<td>350</td>
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<tr>
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<td>1170 LF</td>
<td>350</td>
<td>300</td>
<td>380</td>
</tr>
<tr>
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<td>138</td>
<td>1500 PR</td>
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<td>330</td>
<td>500</td>
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<td>1850 LF</td>
<td>550</td>
<td>590</td>
<td>570</td>
</tr>
<tr>
<td>88 f</td>
<td>150</td>
<td>1230 LF</td>
<td>390</td>
<td>310</td>
<td>480</td>
</tr>
<tr>
<td>92 f</td>
<td>155</td>
<td>920 PR</td>
<td>290</td>
<td>230</td>
<td>320</td>
</tr>
</tbody>
</table>

LF, lateral facet; MF, medial facet; PR, principal ridge; minima and maxima are marked bold.

Fig. 5. Transverse sections through a patella with a focal medial cartilage lesion (arrow): (a) contact radiograph (500 µm section); (b) histological section (100 µm) stained with van Gieson.

**SMZ thickness in specimens with medial and lateral cartilage lesions**

In patellae with medial lesions (Table 3) maxima of 810–1850 µm (mean = 1210±350 µm) were found, and in those with lateral lesions (Table 4) peak values of 930–2450 µm (mean = 1710±610 µm). In the latter, the maxima were always localised in the lateral facet (Fig. 4c), but in the specimens with medial lesions 2 cases were observed in which they were localised at the principal ridge and in 2 at the medial facet (Fig. 4b). In the specimens with medial lesions (Table 3, Fig. 5) the mean thickness varied between 270 and 550 µm (mean = 400±100 µm) and in those with lateral lesions (Table 4, Fig. 6) between 310 and 730 µm (mean = 560±160 µm). The mean lateral thickness was significantly greater than that of the medial facet in the patellae with lateral cartilage lesions ($P < 0.05$), but not in the group with medial cartilage damage. The comparison between normal and pathological specimens showed that whereas those with lateral cartilage damage did not differ significantly from normals, those with medial damage exhibited a significantly lower total and lateral SMZ thickness than the normal specimens ($P < 0.05$) (Fig. 8). The group with medial damage did not, however, show a significantly lower SMZ thickness of the medial patellar facet.

The thickness of the SMZ measured directly beneath the medial cartilage lesions ranged from 200 to 600 µm (mean 390±140 µm), that beneath the lateral cartilage lesions from 470 to 940 µm (mean 670±210 µm). In some cases the medial lesions were accompanied by a local advancement of ossification (Fig. 5), but this was not a consistent finding. The SMZ beneath the lateral cartilage lesions was significantly thicker than that beneath the medial lesions ($P < 0.05$), but at both sites the values were well within the range of those measured in normal patellae (Tables 1, 2). The lateral cartilage lesions were not usually found at the sites of maximal SMZ thickness.

**DISCUSSION**

The questions raised in this study were, whether there exist differences in normal patellar SMZ thickness of males and females, and whether alterations of the local SMZ thickness or of its distribution pattern throughout the joint surface are observed in naturally
Table 4. Thickness of the SMZ in patellae with cartilage lesions at the lateral facet

<table>
<thead>
<tr>
<th>Age (y)</th>
<th>Body size (cm)</th>
<th>Maximum and location of the SMZ thickness (µm)</th>
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<th>Mean of the medial facet (µm)</th>
<th>Mean of the lateral facet (µm)</th>
</tr>
</thead>
<tbody>
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<td>240</td>
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</tr>
<tr>
<td>77 m</td>
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<td>2270 LF</td>
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<td>520</td>
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<td>81 m</td>
<td>166</td>
<td>1760 LF</td>
<td>570</td>
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<td>650</td>
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<tr>
<td>83 f</td>
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<td>1100 LF</td>
<td>490</td>
<td>640</td>
<td>490</td>
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<tr>
<td>83 f</td>
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<tr>
<td>92 m</td>
<td>163</td>
<td>2000 LF</td>
<td>620</td>
<td>450</td>
<td>760</td>
</tr>
</tbody>
</table>

LF, lateral facet; MF, medial facet; PR, principal ridge; minima and maxima are marked bold.

Fig. 6. Transverse sections through a patella with a focal lateral cartilage lesion (arrow): (a) contact radiograph (500 µm section); (b) histological section (100 µm) stained with van Gieson.

occurring, focal, non-full-thickness cartilage lesions. Since the boundary between the calcified cartilage and the subchondral bone layer is highly irregular, and because the calcified cartilage and the subchondral bone layer may be regarded as a morphological, radiographic, and mechanical unit, both layers were measured together rather than separately.

Comparison with previous morphological and biomechanical studies

Roux (1896) was probably the first to observe variations in the thickness of what he called the ‘pressure-receiving plate’ (‘Druckaufnahmeplatte’).
He reported a thickness of 1 mm in patellae of normal subjects, and values around 0.1 mm in an individual who had not used his lower limb for a period of 3 y. Our results show that the patellar SMZ exhibits an inhomogeneous thickness distribution, with maxima of > 2 mm in the lateral facet and values as low as 100 µm at the periphery of the joint. These data complement previous studies in which the trabecular bone underlying the medial patellar facet has been shown to be less dense and to yield a different structural organisation from that of the lateral side (Raux et al. 1975). Even though we find a fairly constant distribution pattern of SMZ thickness, there is considerable variation between individuals with regard to the maximal and mean values. The thickness patterns observed in this study agree in principle with those of the apparent (Pedley & Meachim, 1979) and radiological subchondral bone density (Müller-Gerbl et al. 1989; Eckstein et al. 1992, 1993), and also with those of subchondral bone stiffness (Townsend et al. 1975). They exhibit, however, a greater diversity than the density patterns, probably because in radiological studies the partial volume effect smooths topographic variations of the SMZ.

Pauwels (1963, 1980) suggested that the density of the subchondral bone may be regarded as an ‘embodiment’ of the stress diagram and his view has been supported by x-ray densitometric (Tillmann & Brade, 1980) and CT osteoabsorptiometric studies (Müller-Gerbl et al. 1989, 1994; Eckstein et al. 1992, 1993, 1995). This hypothesis is based on the idea that bone functionally adapts to the long-term stress encountered during normal daily activity (Wolff, 1892), and this has been confirmed in animal experiments (Goodship et al. 1979; Rubin & Lanyon, 1987), photoelastic models (Kummer, 1966; Pauwels, 1990), and finite element analyses (Huiskes et al. 1987; Beaufre et al. 1990). Variations in subchondral bone density and thickness of the femorotibial joint have been shown to be associated with variations in joint loading (Christensen et al. 1982; Shimizu et al. 1993; Milz & Putz, 1994; Armstrong et al. 1995), particularly in genu valgum and varum (Christensen et al. 1982; Müller-Gerbl et al. 1994). It has also been demonstrated that subchondral density patterns are subject to change in the adult following a high tibial osteotomy (Müller-Gerbl et al. 1994), and that strenuous running exercise can increase the subchondral bone thickness in dogs (Oettmeier et al. 1992). For these reasons it appears tempting to derive the long-term loading conditions of joints from the quantitative distribution of the subchondral bone tissue.

Patellar contact-pressure changes dramatically during knee flexion and extension (Ahmed et al. 1983; Hille et al. 1985; Hehne, 1990), in particular in the medial facet, but the proximal lateral facet has been shown always to remain in contact from 60° to 140° of flexion. The lateral facet thus supports the load over a wider range of motion and is used more frequently during normal activity. Also, in a computer model of passive knee flexion (Heegaard et al. 1995), greater stresses were calculated in the lateral patellar facet. These findings are consistent with higher lateral SMZ thickness and it is important to note that the thickness of the SMZ may account for the unique loading pattern of an individual joint and its specific neuromuscular control mechanisms (which is difficult to determine experimentally), and it may therefore be qualified to assess the long-term ‘loading history’ of joints during normal activity.

**SMZ thickness in male and female specimens**

Our study shows that there exist significant differences of SMZ thickness between males and females. Although the ratio between medial and lateral thickness is similar in both sexes, women exhibit a strikingly lower maximal and mean SMZ thickness than men. This contrasts with the findings on patellar subchondral bone density, in which no such differences could be detected (Eckstein et al. 1992). The reasons for the lower SMZ thickness in the women may be their lower body weight, and hence the less severe mechanical loading, but hormonal factors and, in particular, osteoporosis may also play an important role in this issue. Future clinical studies, based on noninvasive imaging techniques, may cast some light on these issues, since they have the advantage that more information about the history of the patient can be obtained.

**SMZ thickness in specimens with medial and lateral cartilage lesions**

Patellar cartilage lesions have been shown to occur very early in life (Aleman, 1928) and to affect a vast proportion of the elderly population (Mitrovic et al. 1987). Nevertheless, there has been much (as yet unresolved) controversy as to the origin of these lesions. Goodfellow et al. (1976) have attributed cartilage degeneration of the medial ‘odd facet’ to its ‘habitual non-contact’ during joint function, and Ficat & Hungerford (1977) lateral cartilage lesions to a so-called ‘excessive-pressure syndrome’. In this
context it should be remembered that the thickness of the SMZ may reflect the dominant loading pattern of the joint, but that it does not account for single (infrequent) loading events that may lead to cartilage degeneration.

In the specimens with lateral cartilage lesions we observed some cases of elevated mean lateral thickness, but this group was not significantly different from normal patellae. At least as far as the given age range is concerned, our data therefore do not support the hypothesis that a greater average pressure acts on the lateral facet of these individuals and that lateral cartilage damage is brought about by a long-term alteration of load distribution between both facets. The progression of the cartilage damage could not be evaluated in this study, but the higher tendency of lateral patellar cartilage lesions to progress with time that has been reported in the literature (Meachim & Emery, 1974) may have to do with the higher thickness of the SMZ in the lateral patellar facet (Abernethy et al. 1978).

Our findings indicate that the patellae with medial damage may have been exposed to an other mechanical environment than normals, since their total mean and lateral mean SMZ thickness (but not their mean medial thickness) is significantly less. This result is consistent with previous findings of decreased overall subchondral bone density and thickness in patients with medial chondromalacia patellae (Darracott & Vernon-Roberts, 1971; Eckstein et al. 1993) and indicates that insufficient joint use may be a promoting factor for medial patellar cartilage damage. Animal experiments have shown that osteoarthritic changes can follow a reduction in intermittent joint loading and that these changes are preceded by a decrease in bone density (Smith et al. 1992). With mechanical disuse the proteoglycans may decrease (Smith et al. 1992; Kiviranta et al. 1994), the cartilage having an impaired ability to withstand normal levels of physiological loading. The significantly lower mean lateral (but not medial) SMZ thickness in this group indicates that the long-term stress distribution between the medial and lateral patellar facet may be different from normal subjects, and the imbalance may result from an unusual neuromuscular innervation pattern of the quadriceps femoris (Weh & Eickhoff, 1983). One may therefore speculate that medial patellar cartilage lesions are promoted by infrequent, high-magnitude stress peaks during deep knee flexion (Hehne, 1990), and these may be particularly critical in mechanical disuse, in which the cartilage is more vulnerable (Kiviranta et al. 1994).

It has previously been suggested that a thickening of the subchondral bone plate may be an important initial step towards cartilage degeneration, before changes occur in the cartilage itself (Radin et al. 1970, 1972, 1978, 1991; Simon & Radin, 1972; Brown et al. 1984; Shimizu et al. 1993). Although we could directly assess neither the mechanical behaviour of the subchondral bone nor the time sequence of events at the beginning of cartilage lesions, our results suggest that focal, non-full-thickness cartilage damage is found in areas of both high and low subchondral bone thickness, and that the values recorded there are in the range of those beneath healthy, undamaged cartilage. In this context, it should also be remembered that the stiffness of subchondral bone (Choi et al. 1990; Mente & Lewis, 1994) is several orders of magnitude higher than that of the uncalcified cartilage and that therefore subtle changes in its mechanical properties will probably not affect the mechanical stresses within the cartilage matrix.

Animal models of osteoarthritis (Simon & Radin, 1972; Benske et al. 1988; Layton et al. 1988; Dedrick et al. 1991, 1993, 1995; Armstrong et al. 1994) have yielded contradictory results regarding local changes of the subchondral bone thickness in cartilage degeneration, probably because different species, different joints, and different models of osteoarthritis were used. However, in contrast to previous studies of the human hip (Chai et al. 1991; Grynpas et al. 1991) we can show that naturally occurring, focal, non-full-thickness lesions of the patellar cartilage may appear in areas of high as well as those of low SMZ thickness and are not necessarily associated with systematic thickness changes of subchondral bone.

Conclusions

Our findings suggest that males and females show a similar distribution pattern of SMZ thickness, but that the maximal and mean values are significantly lower in women than in men. In elderly subjects, naturally occurring, focal, non-full-thickness cartilage lesions of the patella appear not to be associated with a systematically higher or lower local SMZ thickness. However, specimens with medial cartilage lesions show some differences in the regional distribution pattern of SMZ thickness, indicating a potential alteration in the long-term mechanical loading. Valuable insights into joint function and pathology may be gathered from an analysis of the SMZ thickness distribution throughout the entire joint, and these should be extended in the future to individuals with a well-documented medical and social history.
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