Effects of weight bearing on the tidemark and osteochondral junction of articular cartilage

Histomorphometric analyses of 7 normal femoral heads

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To study the effect of weight bearing on the tidemark and osteochondral junction, we compared the morphology of these two boundaries in weight-bearing and less weight-bearing regions of normal human femoral heads. We measured the irregularities of the boundaries in the two regions using an X-Y digitizer connected to a computer in histological whole sections of femoral heads in 7 subjects without joint diseases.

The irregularity of the tidemark was small, showing no difference between the two regions. However, the irregularity of the osteochondral junction in the weight-bearing region was greater than in the less weight-bearing region, which was confirmed by three-dimensional reconstructed images. Our findings suggest that mechanical stresses greatly influence the morphology of the osteochondral junction compared to the influence of such stresses on the tidemark, and that the marked irregularity of the osteochondral junction in the weight-bearing region is a reactive phenomenon against mechanical fragility due to simple contact between calcified cartilage and subchondral bone without fibrous connections.

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The boundary between the non-calcified and calcified cartilage and that between the calcified cartilage and subchondral bone of human adult articular cartilage are called the tidemark and osteochondral junction, respectively. Since these two boundaries are the contact areas between tissues with various biochemical constitutions, stresses on the articular cartilage usually affect these boundaries. Many studies have examined the relationship between the magnitude of mechanical stresses and the morphology of the tidemark or the calcified layer (Green et al. 1970, Stougard 1974, Lane et al. 1977, Bullough and Jagannath 1983, Meachim and Allibone 1984, Bullough et al. 1985, Müller-Gerbl et al. 1987, Flygare et al. 1993). However, few studies have described the relationship between stresses and the morphology of the osteochondral junction (Müller-Gerbl et al. 1987, Hough et al. 1974, Oegema and Thompson 1995). Therefore, we compared the morphology of these two boundaries, the tidemark and osteochondral junction, in weight bearing and less weight-bearing regions of human femoral heads to evaluate the effects of weight bearing on such boundary structures.

Material and methods

Femoral heads obtained from patients with femoral neck fractures who underwent endoprosthetic replacement surgery were examined. The femoral heads, removed within 1 week after fracture, met the following criteria: the subjects had no gait disturbance before fracture; had no abnormalities were detected on radiographs of the bilateral hip joints including osteoarthrotic changes, subchondral bone erosion or acetabular dysplasia; the surface of the femoral head articular cartilage was macroscopically smooth. 7 femoral heads that fulfilled these criteria were used as samples. The mean age of the patients was 74 years (Table).

To determine the correct anatomical orientation of the fractured femoral heads, they were reduced

The means (95% confidence intervals) of the tidemark and osteochondral junction irregularities of weight-bearing and less weight-bearing regions in 7 cases

			Tidemark irregularity		Osteochondral junction irregularity	
Case	Age	Gender	WB region	Less WB region	WB region	Less WB region
1	56	F	1.10 (1.07–1.12)	1.27 (1.21–1.34)	1.56 (1.45–1.67)	1.19 (1.13–1.25)
2	67	M	1.13 (1.11–1.15)	1.15 (1.11–1.19)	1.42 (1.32–1.53)	1.20 (1.11–1.29)
3	70	M	1.13 (1.11–1.14)	1.14 (1.10–1.18)	1.34 (1.24–1.44)	1.13 (1.08–1.18)
4	76	M	1.18 (1.15–1.21)	1.05 (1.04–1.06)	1.24 (1.18–1.31)	1.06 (1.04–1.07)
5	79	M	1.12 (1.07–1.16)	1.09 (1.06–1.12)	1.63 (1.46–1.80)	1.13 (1.07–1.19)
6	82	F	1.09 (1.08–1.11)	1.13 (1.09–1.16)	1.97 (1.72–2.23)	1.36 (1.20–1.53)
7	87	F	1.09 (1.08–1.11)	1.13 (1.10–1.16)	1.29 (1.22–1.36)	1.04 (1.03–1.05)
Average			1.12 vs [a]	1.14	1.50 vs [b]	1.15

WB weight bearing
[a] NS
[b] $p < 0.001$

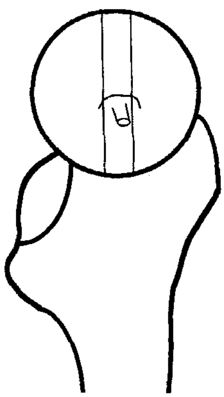
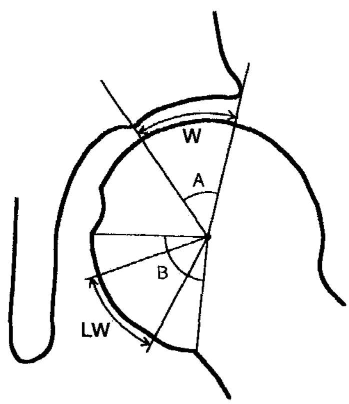


Figure 1. Diagram showing a cutting plane of femoral heads.

Figure 2. Diagram showing the regions (W, LW) of measurement which are determined by open angles (A, B), respectively. The open angle (A) is the angle between the two lines connecting the medial and lateral margins of the lunate surface and the center of the femoral head. The open angle (B) is the angle between the two lines connecting the center of the head and the inferior margin of the fovea centralis or the inner bone-cartilage junction of the femoral head. Region LW corresponds to 1/2 of the open angle (B); it is located in the center of two lines.



to normal position during surgery and the anterior and posterior aspects were marked. Using these marks and the fovea centralis of heads as landmarks, we cut the resected femoral heads, using a band saw, into sections 1 cm thick around the middle of the frontal plane of the femoral head (Figure 1). The sections were fixed in 10% formalin in phosphate-buffered solution at pH 7.0 and decalcified in phosphate-buffered 10% ethylene diamine tetra-acetic acid at pH 7.1 according to Hillemann and Lee (1953). Subsequently, the decalcified femoral heads were dehydrated, embedded in paraffin and stained with hematoxylin and eosin after being cut into frontal sections 10 μm thick.

Using frontal radiographs taken in a neutral position with respect to rotation, adduction and abduction of the femoral head on the unfractured side, we determined the open angles (A)and (B) (Figure 2). With use of the fovea centralis of the femoral head, the bone-cartilage junction inside or outside the femoral head and the trabecular pattern as indices, totally sectioned samples of the femoral heads were overlapped on respective radiographs of the femoral head of the unfractured side, and region W corresponding to open angle (A), was determined. Next, region LW, corresponding to 1/2 of open angle (B), was established in the center, between the inferior margin of the fovea centralis of the femoral head and the inner bone-cartilage junction.

Photomicrographs (× 25) were taken from the deep layer of articular cartilage to the subchondral bone in regions W and LW. Photomicrographs of

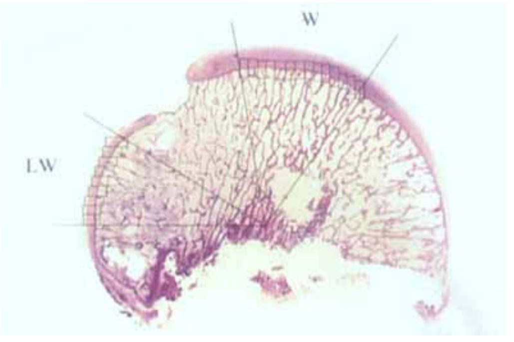


Figure 3. Photomicrograph showing sequential segments of W and LW regions for histomorphometry on a histological section.

region W were taken in 12–14 segments, while those in region LW were taken in 8–10 segments (Figure 3). These photomicrographs were enlarged 5 times and then printed. We determined the actual length of the wavy lines indicating the tidemark and osteochondral junction observed in the respective enlarged photomicrographs by using an X-Y digitizer connected to a computer. Taking care to avoid overlapping the region of measurement, we determined the irregularity of the wavy lines by dividing the actual length by the width of the region measured. The mean values of these parameters were obtained for regions W and LW of the respective specimens. Next, photographs of totally sectioned specimens of the femoral head were enlarged 5 times and the area of overall layers of the articular cartilage in regions W and LW was determined with an X-Y digitizer connected to a computer. Then we determined the thickness of the articular cartilage by dividing the area by the width of the region of measurement. Subsequently, the irregularity of the wavy lines and the thickness of the articular cartilage were compared in regions W and LW.

Data concerning the irregularities were analyzed with ANOVA for the repeated measurement using the SPSS software program (version 8.0J, SPSS, Inc., Chicago, IL, USA). The Wilcoxon signed-rank test was used to deremine the significance of the difference in the thickness of the articular cartilage between two regions. A p-value less than 0.05 was considered significant.

Furthermore, small pieces of the cartilage, 0.5 × 0.5 cm with subchondral bone, were cut from weight-bearing and less weight-bearing regions of the femoral head in case 3 to obtain 7 μm thick serial sections in the frontal plane. 1 of the 5 serial sections was systematically selected, and the wavy lines of the osteochondral junction obtained from a total of 40 sections were put into a computer, and three-dimensional images of these wavy lines, which were surface images of the subchondral bone endplate, were simulated, using the system constructed by Inoue et al. (1992).

Results

Open angles A and 1/2 B, used as indices to establish weight-bearing and less weight-bearing regions, had almost constant values, with no wide variation between the patients. The mean of open angles A and 1/2 B of 7 samples was 41 (95% CI: 40–43) degrees and 32 (95% CI: 28–35) degrees, respectively.

No specimens had cracks in the tidemark or the osteochondral junction in the regions of measurement. On histologic examination, no osteoarthrotic changes, such as fibrillation or fissures, were found in any sample.

The irregularities of the tidemark did not differ between the W and LW regions. However, the irregularity of the osteochondral junction differed significantly between the two regions ($p < 0.001$, Table). These findings were confirmed by histology (Figure 4).

The mean thicknesses of the articular cartilage in regions W and LW were2.20 (95% CI: 1.80–2.60) mm and 1.44 (95% CI: 1.21–1.66) mm, respectively ($p = 0.02$).

Markedly different three-dimensional images of the osteochondral junctions were simulated in the two regions—that is, a more irregular junction was simulated in region W, while a less irregular junction was simulated in region LW (Figure 5).

Discussion

In this study, we determined the more and less weight-bearing regions of the femoral head by using the results of biomechanical experiments reported by Greenwald and Haynes (1972), which

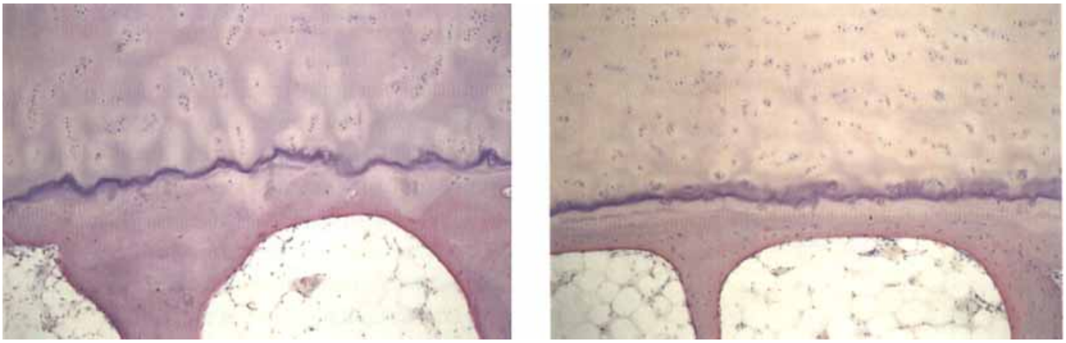


Figure 4. HE stained sections (× 100), taken from regions W (left) and LW (right), showing a definite difference in the irregularities of the osteochondral junction between the two regions.

corresponded to the two regions defined by Meachim and Allibone (1984). To compare the morphology of the tidemark and osteochondral junction in these two regions, we prepared totally sectioned specimens to reduce the differences due to the process of sample preparation of the two regions. Furthermore, accurate localization of the two regions was possible, using samples sectioned in this way.

It is well known that articular cartilage of the femoral head is thicker in more heavily loaded areas and our findings agreed with this fact.

Meachim and Allibone (1984)reported that the tidemark irregularity of the less weight-bearing region was larger than that of the weight-bearing region. In contrast, some studies have reported that the tidemark irregularity of normal articular cartilage was close to 1, showing no difference between weight-bearing and less weight-bearing regions (Müller-Gerbl et al. 1987, Oegema and Thompson 1995). Our findings almost corresponded to these studies, and demonstrated that the tidemark irregularity of the articular cartilage with a normal surface was small, regardless of the magnitude of the loads and it was not affected by mechanical stresses.

Although it has been suggested that the irregularity of the osteochondral junction was greater than that of the tidemark (Müller-Gerbl et al. 1987, Oegema and Thompson 1995), no studies have yet evaluated the relationship between the irregularity of the osteochondral junction and the magnitude of the loads after quantification of the irregularity. We found a greater irregularity of the osteochondral junction in the weight-bearing region than in the less weight-bearing one.

The tidemark is the boundary between non-calcified and calcified layers, and collagen fibers, which bind two layers, are present in the tidemark (Redler et al. 1975, Teshima 1978). Hough et al. (1974) suggested that there is a relationship between the cartilage and bone bridged by unrav-

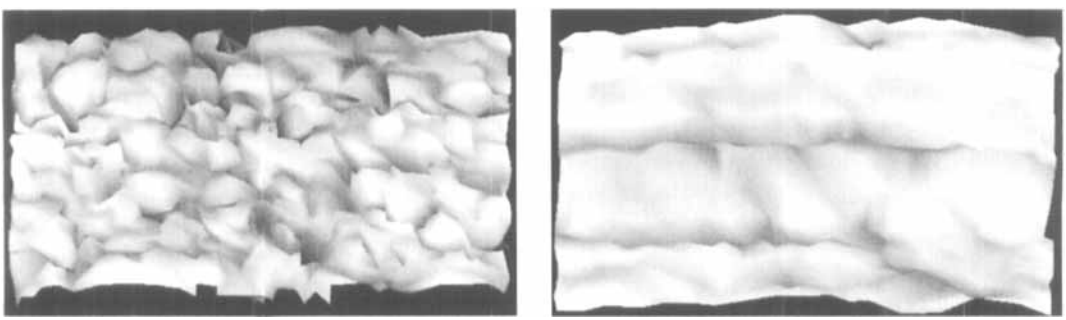


Figure 5. Three-dimensional images of the surface of the subchondral bone endplate (× 60). Irregular monticulus elevations measuring 0.1–0.2 mm in diameter were simulated in region W (left), while gentle-sloping hill-like images were simulated in region LW (right).

elled collagen fibrils in the osteochondral junction. However, some studies have reported that no linear fibrous connections are present between the calcified cartilage and bone because the types of collagen are different in the two structures (Redler et al. 1975, Oegema and Thompson 1995). Radin and Rose (1986) proposed that the function of the irregularity is to increase the binding between calcified cartilage and subchondral bone after converting shearing stresses loaded on the osteochondral junction into pressure and tension. Therefore, the irregularity of the osteochondral junction in the weight-bearing region is considered a reactive phenomenon against mechanical fragility, due to simple contact between the two tissues without fibrous connections. In other words, the irregularity of the osteochondral junction may be determined by the magnitude of loading stresses.

In agreement with the results reported by Wampler et al. (1980) and Clark and Huber (1990), we found that the irregularity of the osteochondral junction was formed by monticulus elevations of the subchondral bone. They proposed that blood vessels were present at the center of the elevations and that such elevations were formed circumvascularly. The subchondral bone endplate is the cortical bone, accompanied by the haversian systems (Mankin 1963). The mean diameter of the haversian systems in adult humans is reported to be 0.19 mm (Parfitt 1983), which corresponds to the diameter of monticulus elevations (0.1–0.2 mm). Lane et al. (1977)reported that increased vascularity was present in heavily loaded areas of the subchondral bone of the femoral head as well as an increased remodeling activity. Great irregularity of the weight-bearing region of the osteochondral junction, which was found in this study, was ascribed to remodeling of the subchondral bone.

The morphology of the osteochondral junction of joints, including the ankle and knee, where joint movements are limited to one direction of flexion and extension, may differ from that in the hip, because of the limited direction of mechanical stresses. Furthermore, changes with age and those due to osteoarthrosis remain to be elucidated.

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