

TRABECULAR ARCHITECTURE OF THE KNEE JOINT

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The trabecular architecture of the human knee joint was studied three dimensionally by microradiography. The trabecular arrangement of the two condylar wheels of the femur was divided into five types. The trabeculae are so arranged that both condyles are able to adjust to mechanical compression and rotary movement. In the tibia, each trabecular arrangement has a different mechanical function. The epiphyseal line can be considered a laminated structure interposed between the compressive forces acting from the articular surface and the forces supporting the architecture of the metaphysis. The mechanics and kinematics of the trabecular architecture are discussed.

Key words: trabecular architecture; knee joint; microradiography

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Various attempts have been made to analyze the trabecular structure of the upper end of the femur. The oldest model is Ward's triangle (trigonum internum femoris) described in 1838 in which it was likened to a derrick supporting a load. The trabecular architecture of the femoral head and neck has been used in biomechanical analysis of osteoarthritic alterations of the hip, internal fixations of fractures, osteotomy of the proximal femur and in total hip replacement. However, the trabecular architecture of the knee joint has not been analyzed in a similar fashion. The purpose of this paper is to describe knee trabecular architecture as observed by microradiography.

MATERIAL AND METHODS

Six complete adult knee joints were obtained from amputated limbs. The patients ranged from 30 to 60 years of age. The specimens were fixed

in 10 per cent formalin for 1 week, and the soft tissues were removed from the femur, tibia and patella. The specimens were washed in water for 24 hours; defatted in trichlorethylene for 72 hours; dehydrated for 24 hours in a graded series of 70, 90 and 99 per cent ethyl alcohol; dried at room temperature for 4 hours and embedded in polyester resin. The embedded specimens were cut into serial sections, using a high speed cutter, in the horizontal, sagittal and frontal planes. The sectioned specimens were treated with 2 per cent sodium hypochlorite solution for 20 minutes to remove the protein. The embedded resin was removed manually and the bone sections were examined by microradiography. The microradiographic apparatus used was type CMB, Nippon Soft-X Co. (Tokyo). Roentgenograms were taken at 30 KVP, 2.5 mA, for 90 seconds at a distance of 70 cm.

RESULTS

The femur and tibia trabeculae showed different patterns of arrangement on either side of the epiphyseal line on sagittal sections. Below the epiphyseal line in the femur, the trabeculae were gen-

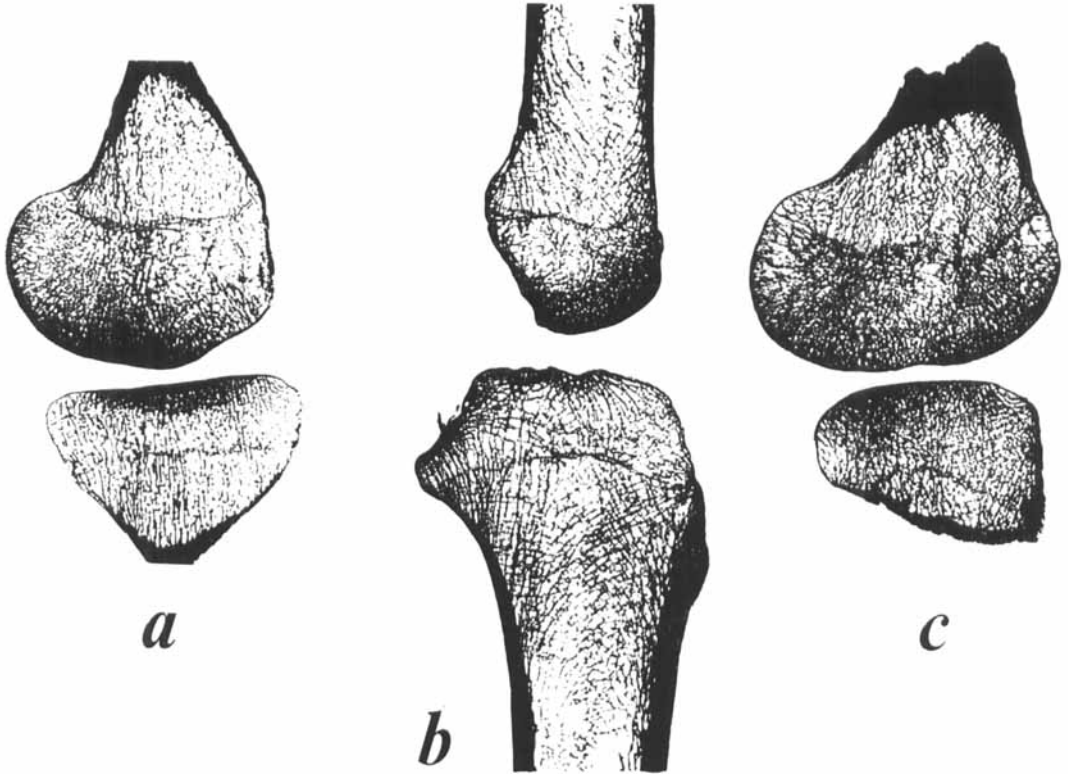


Figure 1. Sagittal sections of the knee joint, 40-year-old female. a, medial section; b, middle section; c, lateral section.

erally arranged perpendicular to the articular surface. In the medial and lateral condyles, dense orientations of the trabeculae ran directly from the middle and somewhat posterior region of the epiphyseal line to the posterior joint surface. This trabecular orientation had an anterior inclination of 20° to the femoral axis. Trabeculae located posterior to this region were arranged perpendicular to the joint surface in both condyles. However, trabeculae located in the anterior area displayed different patterns in the medial and lateral condyle. Trabeculae in the medial condyle were mainly arranged perpendicular to the joint surface toward the epiphyseal line. These trabeculae were fine and dense for 5–10 mm from the articular surface, and then thick and coarse toward the epiphyseal line. These thick and coarse trabeculae

were connected by fine transverse trabeculae. In the lateral condyle, the trabeculae were also arranged perpendicular to the articular surface but did not reach the epiphyseal line, and these trabeculae were consistently thick and dense. No definite trabecular orientation was present in the region surrounded by the posterior trabeculae, the anterior trabeculae and the epiphyseal line.

In these sagittal sections the profile of the medial condyle was more circular and the lateral condyle was more ellipsoidal in shape (Figure 1). As the wheels of both condyles were not parallel to the sagittal plane, both condyles were sectioned in the plane parallel to the wheel. The medial sections of the medial condyle (Figure 2) were more circular but at the center of the wheel a more ellipsoidal contour was present. In cut-sections

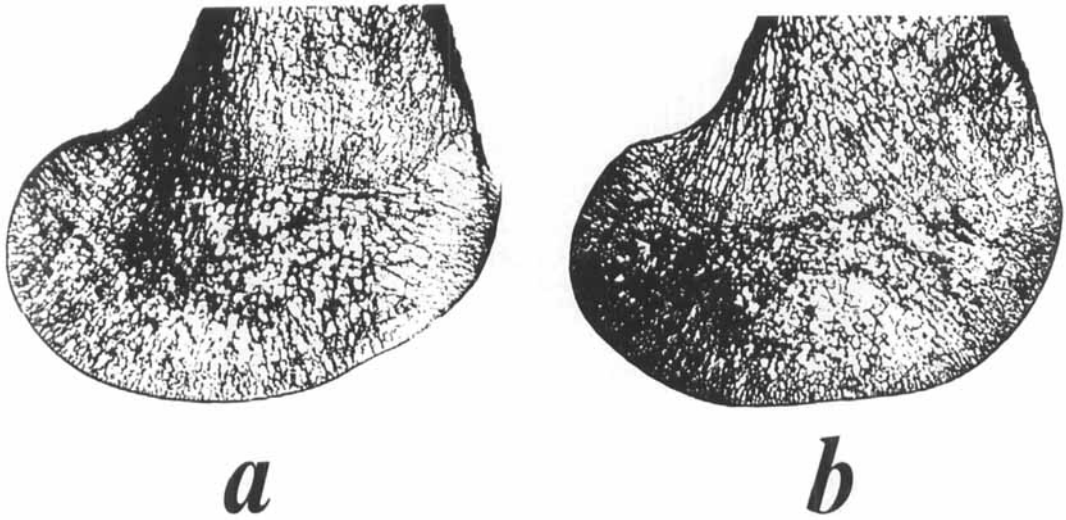


Figure 2. Sections of the condylar wheels, 36-year-old male. a, medial condyle; b, lateral condyle.

near the intercondylar notch the contour was ellipsoid-shaped with a flattened anterior surface. The contour of the lateral condyle was more smoothly ellipsoidal. The trabecular arrangement of the condylar wheels was similar in both condyles. The previously described trabeculae with 20° inclination were also evident in both condyles. From the patellar surface of the condyles, the fine and dense perpendicular trabeculae were arranged toward the epiphyseal line. These trabeculae were arranged more horizontally in the medial than in the lateral condyle. In the central area of these wheels the trabeculae formed an irregular network. These trabeculae were thick and coarse in the medial condyle but fine and dense in the lateral condyle. The irregularly shaped intercondylar notch showed articular cartilage in the anterior half. The trabeculae were perpendicular to the surface in the anterior half but formed a network in the posterior half. Above the epiphyseal line, the trabeculae were parallel to the femoral axis in both condyles. However, sections of the intercondylar notch showed two groups of trabeculae crossing each other: those running from

the antero-superior cortex to the postero-inferior cortex and those from the postero-superior cortex to the antero-inferior cortex.

Sagittal sections of the patella showed two groups of trabeculae (Figure 3). The first group was arranged perpendicular to the articular surface in a rather postero-anterior direction and the second group ran along the anterior contour at intervals of 4 mm.

Trabeculae of the tibia were arranged perpendicular to the joint surface in both condyles and they were parallel to the tibial axis. However, sagittal sections of the middle area of the tibial tuberosity showed four definite groups of trabecular arrangement: (1) from the tibial tuberosity to the posterior articular surface; (2) from the posterior cortex to the posterior articular surface and eminentia; (3) from the tibial tuberosity downward to the posterior cortex and (4) from the anterior cortex upward to the posterior margin of the metaphysis. The trabeculae of the last group were finer than those of the other groups, and the latter two groups crossed each other in the metaphysis.

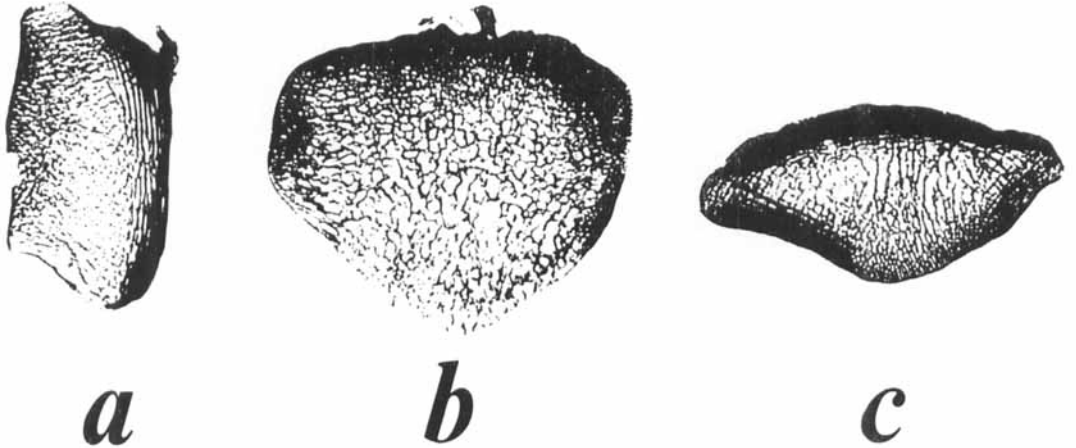


Figure 3. Sections of the patella. a. sagittal section, 40-year-old female; b. frontal section, 60-year-old male; c. horizontal section, 34-year-old male.

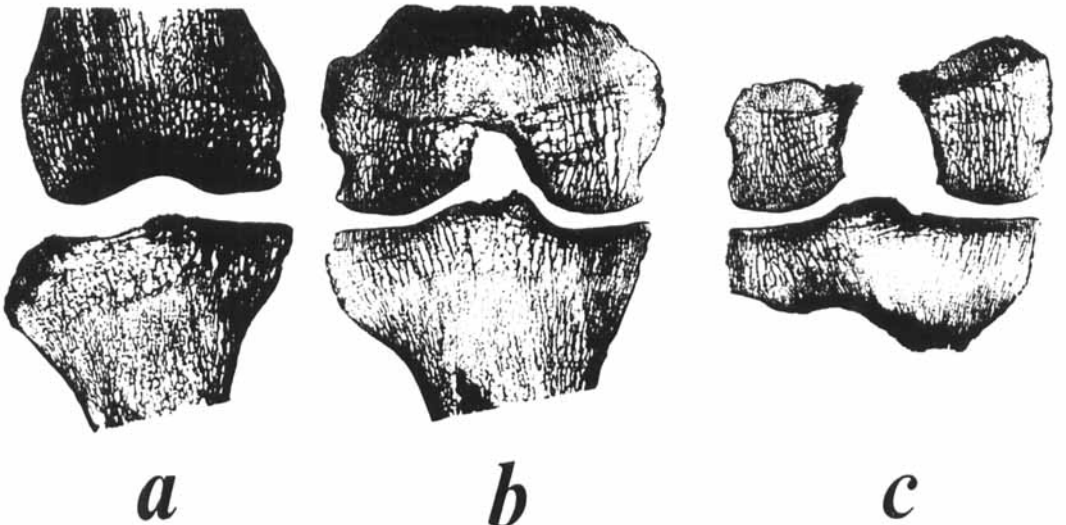


Figure 4. Frontal sections of the knee joint, 60-year-old male. a. anterior section; b. middle section; c. posterior section.

In frontal sections of the femur and tibia, the trabeculae were usually arranged perpendicular to the joint surface and parallel to the bone axis (Figure 4). They were thicker and coarser near the epiphyseal line from the joint surface, and finer and denser toward the metaphysis. Other trabeculae radiated from the intercondylar notch toward both condyles.

Frontal sections of the patella showed

an irregular trabecular network (Figure 3).

Horizontal sections of the femoral condyles showed the direction of the condylar wheels (Figure 5). The patello-femoral articulation was also observed in these sections. All horizontal sections of the femoral condyle showed four patterns of trabecular orientation. The first pattern was from the posterior articular surface of both condyles to the patellar

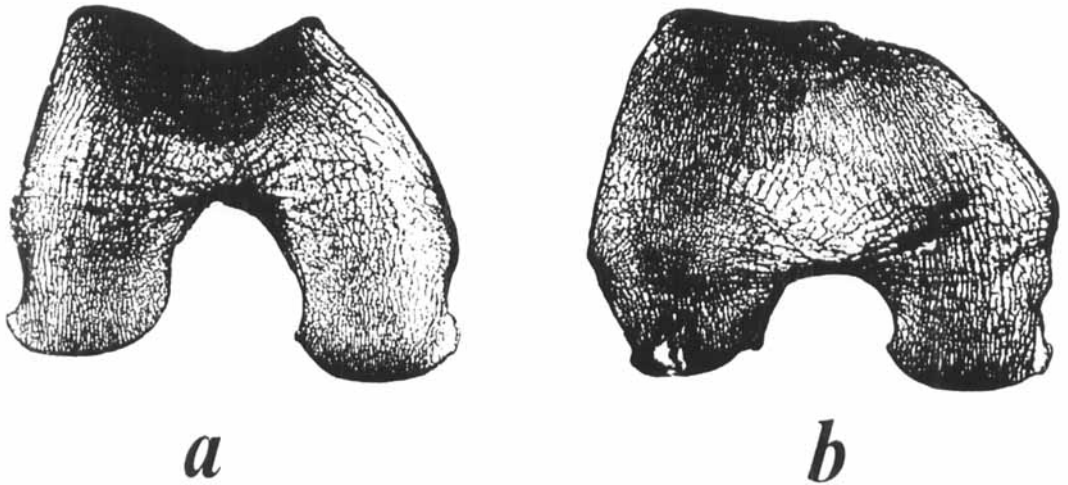


Figure 5. Horizontal sections of the femur, 34-year-old male. a. section below the epiphyseal line; b. section above the epiphyseal line.

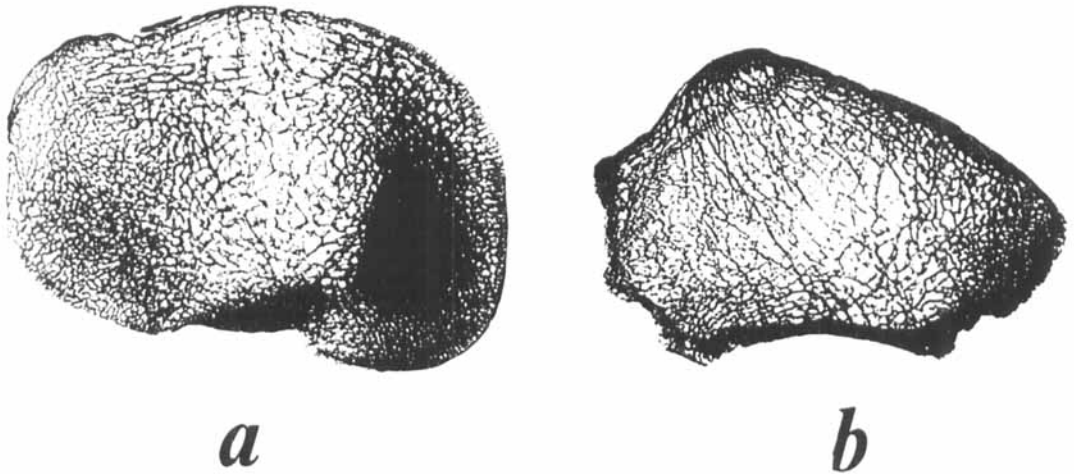


Figure 6. Horizontal sections of the tibia, 34-year-old male. a. section above the epiphyseal line; b. section below the epiphyseal line.

surface, and the trabeculae were arranged parallel to the outer contour of the condyles. The trabeculae perpendicular to the posterior surface were fine and dense near the joint surfaces, but thick and coarse in the region between the joint surfaces. The second type of trabecular arrangement was found near the patellar surface and was oriented parallel to the anterior contour, crossing the first type of trabeculae. The third

type of trabecular arrangement radiated from the intercondylar notch out to both sides, crossing the first type of trabeculae. The central area of the femur surrounded by the first, second and third trabecular arrangements was rather coarse and irregularly oriented. The fourth type of trabecular arrangement consisted of fine and short trabeculae radiating from both collateral ligament attachments.

Horizontal sections of the patella showed three types of trabecular arrangement. The first was fine, ran antero-posteriorly and was perpendicular to the joint surface. The second trabecular group was arranged along the anterior contour at intervals of about 4 mm. The third type was present mainly at the lateral joint surface and was arranged parallel to the contour at intervals of 4–5 mm (Figure 3).

Horizontal sections of the tibia near the articular surface showed a fine trabecular network with a transverse orientation in the anterior area and a radial orientation in the posterior area (Figure 6). Four groups of trabecular arrangement were found in sections containing the tibial tuberosity. The first group ran from the lateral cortex to the tibial tuberosity, the second from the postero-medial cortex to the tibial tuberosity, the third from the posterior cortex to the antero-lateral cortex and the fourth from the posterior cortex to the antero-medial cortex.

DISCUSSION

The architecture of cancellous bone has been studied for the past one hundred years. In 1867, Meyer observed the architecture of the upper end of the femur and described two kinds of trabecular arrangement, viz., tension trajectories and pressure trajectories which intersected at right angles. In 1869, Wolff demonstrated the relation between architecture and function of bone and emphasized that the major trabecular patterns intersect at right angles (orthogonality). Roux (1895) agreed with Wolff's opinion and stated that cancellous bone is built trajectorially.

These theories have been called "the trajectorial theory". The term "trajectory" has been used for a single bone trabecula with a definite orientation corresponding to stress. Gebhardt (1910)

and Petersen (1927) studied the same subject.

However, in 1920, Jansen pointed out that most of the previous investigators considered that the static pressure of the body weight played the predominant role in bone formation. He suggested that muscle tension had an equally strong deciding influence on the architecture of cancellous bone. In 1929, Carey stated that the architecture of cancellous bone was the result of pressure factors from muscle action rather than the static pressure of body weight. Both Jansen and Carey believed that the major trabeculae do not intersect at right angles.

Recently, Pauwels (1973) proved that the classical trajectorial theory is a valid principle for bone architecture in the upper end of the femur.

On the other hand, in 1922, Triepel (1922 a) stated that the internal bone architecture was in basic harmony with the outer contour though further modifications were due to mechanical stress. Triepel's theory was that the trabeculae supported the outer contour of the bone.

Although most of these studies were carried out on the upper end of the femur, it appears to have been accepted that trajectorial architecture was observed in every cancellous bone. Observations of the trabecular patterns in the lower end of the femur have only been reported by a few authors. Koch (1917) studied trabecular architecture in this part using a few three dimensional sections and concluded that all trabeculae arising from the joint surface were perpendicular to it. Jansen (1920) observed the diverging trabeculae radiating from the intercondylar notch and suggested that these might be the result of some rotational force acting on the tibia. Triepel (1922 b) found that the cut-surface of the femoral condyles displayed two trabecular orientations, one running straight from the posterior area diverging to the distal anterior region and the other run-

ning from the anterior area curving along the outer contour of the condyles to the posterior area. He thought that these orientations corresponded with the cut-surfaces of his "contour-forming trabecular sheets". Maquet (1976) studied the trabecular architecture of the femoral condyles using a photoelastic model of frontal and horizontal planes as well as horizontal X-ray pictures and supported the trajectorial theory. Descriptions of the trabecular architecture in the frontal and horizontal plane by Koch, Jansen, Triepel and Maquet were almost the same.

The present study also found trajectories in the frontal and horizontal sections of the femoral condyles as previous investigators have mentioned. These findings suggest that the static pressure of the body weight is important and support the trajectorial theory as did Maquet's findings. However, the precise architecture of both the condylar wheels should be studied in the sagittal plane in order to analyze the relation between their architecture and function. In the usual lateral view of X-ray examinations both femoral condyles and the intercondylar notch are superimposed so that the detailed trabecular architecture cannot be obtained. By contrast, the trabecular architecture of the condylar wheels can be revealed by microradiographic techniques using the recent advances in calcified material preparation. The present study showed that the internal structure of the condylar wheels is influenced by rotary movement in the sagittal plane. Moreover, the plane of the cross-section was made parallel to the direction of each condylar wheel of the femur in this study, because both the condylar wheels of the femur induce rotary movement of the knee joint. The five trabecular arrangements in the sagittal sections are shown in Figure 7.

1. The central network just below the epiphyseal line. These trabeculae were

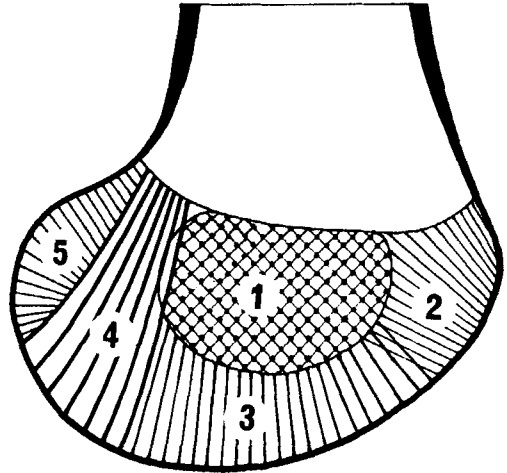


Figure 7. Schematic illustration of the trabecular arrangement of the condylar wheel. 1. Central network. 2. Anterior perpendicular trabeculae. 3. Inferior perpendicular trabeculae. 4. Trabeculae with an anterior inclination. 5. Posterior trabeculae.

the same as the transverse trabeculae observed on vertical cut surfaces radiating from the intercondylar notch to both condyles in both horizontal and frontal sections.

2. The perpendicular trabeculae running from the anterior patello-femoral articular surface to the central network.

3. The perpendicular trabeculae at the bottom of the wheels. They run from the tibio-femoral weight-bearing surface to the central network.

4. Trabeculae with an anterior inclination of 20° .

5. The fine and dense trabeculae seen at the posterior margins of both condyles.

Trabecular arrangement 1 can be likened to the axis of a wheel and trabecular arrangement 3 can be compared to the spokes of a wheel. Arrangement 2 resists compression exerted by the patella, arrangement 4 supports both the weight-bearing-force and the outer contour of the bone, and arrangement 5 supports the outer contour. Some trabeculae perpendicular to the joint surface prob-

ably do not radiate from the axis as the shape of the condylar wheels is not circular. Nevertheless, the present findings demonstrate that both condyles are adjusted to mechanical compression and the rotary movements of the condylar wheels. From these observations it would seem to be difficult to adapt the trajectorial theory to explain the architecture of the condylar wheels.

The present results further indicate that the trabeculae perpendicular to the joint surfaces of both tibial condyles support compression from both condylar wheels of the femur. However, sections containing the tibial tuberosity present a different trabecular arrangement. In 1900, Albert described the trabecular arrangement in these areas as consisting of two groups of trabeculae, viz., an anterior band from the lower posterior cortex to the eminentia and the anterior articular surface, and a posterior band from the lower anterior cortex to the eminentia and the posterior articular surface. He also mentioned that these two bands cross each other at right angles. His study supported the trajectorial theory. The present study also showed trajectories but the trabecular arrangement can be divided into four groups (Figure 8). The first and third groups are constructed to resist tension from the M. quadriceps femoris at the tibial tuberosity and the fourth group to resist tension from the hamstrings. The second trabecular group as well as the posterior half of the first group support compression by acting on the articular surface. Thus, each trabecular arrangement has a different mechanical function. The first and second groups seen in horizontal sections support tension exerted at the tibial tuberosity and the third and fourth groups support the outer contour of the bone.

It was also shown that there are fine and dense trabeculae converging toward the epiphyseal line from the metaphysis

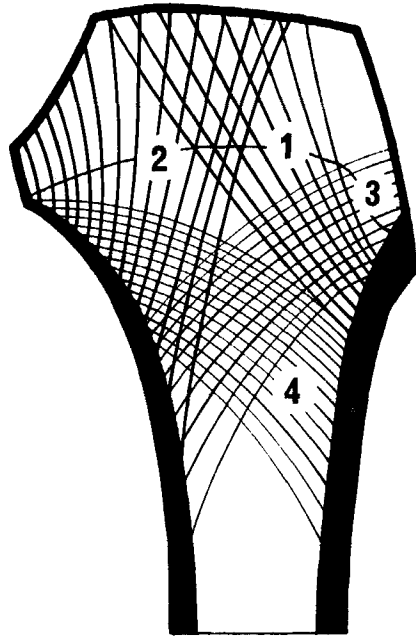


Figure 8. Schematic illustration of the trabecular arrangement of the tibia at the tibial tuberosity. 1. Trabeculae from the tibial tuberosity to the posterior articular surface. 2. Trabeculae from the posterior cortex to the posterior articular surface and eminentia. 3. Trabeculae from the tibial tuberosity inferior to the posterior cortex. 4. Trabeculae from the anterior cortex superior to the posterior margin of the metaphysis.

of both the femur and tibia. The epiphyseal line can be considered a laminated structure interposed between the compressive forces acting from the articular surface and the forces supporting the architecture of the metaphysis.

In 1975, Raux et al. analysed the trabecular architecture of the patella at the microscopic level and concluded that the predominant trabecular elements were the oriented sheets of hard tissue connected laterally by rods of the same structure. In the present study, the main trabeculae of the patella observed in the sagittal and horizontal sections can be said to support compression by acting on the femoral joint surface. The network seen in the frontal sections probably corresponds to the cut surface of these trabeculae. The thick and dense anterior

trabeculae support the tension of the patellar ligament.

The thickness and density of the trabeculae are probably determined by the degree of compression and tension, and the trabecular orientations are probably determined by stresses. Theoretically, the trabecular architecture can be thought of as a kind of rigid frame in solid mechanics. The elements of this rigid frame are the trabeculae which are made of osseous tissue, a kind of composite material. The crossing patterns of this rigid frame are not always rectangular as described in the trajectorial theory and seem to be rectangular only where static pressure plays the predominant role. It appears possible to use the finite element method of solid mechanics for examining the mechanical characteristics of the trabecular architecture.

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