THE STRUCTURE AND FUNCTION OF THE PROXIMAL END OF THE FEMUR

R. S. GARDEN, PRESTON, ENGLAND

From the Orthopaedic Department, Preston Royal Infirmary

The familiar outline of the proximal end of the femur is characterised by its almost spherical head, slightly flattened neck and two trochanters with their communicating intertrochanteric ridge (Fig. 1). Frontal section of the uppermost third of the femur shows the powerful cortex and fragile medulla of the shaft (Fig. 2). Above the lesser trochanter this arrangement is reversed, and a thin cortical shell clothes the dense arrangement of cancellous bone which forms the internal weight-bearing system in the neck and head (Fig. 3).

INTERNAL WEIGHT-BEARING SYSTEM

The calcar femorale, or as Bigelow (1900) described it "the true neck of the femur," is a vertical plate of bone lying deep to the lesser trochanter. The calcar forms the distal anchorage of the medial arrangement of trabeculae in the internal weight-bearing system, sometimes known as the compression group, which streams upwards to end fan-wise at the articular margin of the head. The lateral arrangement of trabeculae, sometimes known as the tension group, arises from the lateral femoral cortex and curves upwards and medially to merge with the compression group in the femoral head. A third group of trabeculae springs from the medial aspect of the cortex at the level of the lesser trochanter to decussate with the lateral trabeculae at the junction of neck and shaft. Enclosed within these trabecular systems is the area of lessened density known as Ward's triangle.

This interpretation of the internal weight-bearing system derives largely from Ward (1838) and from the radiographic appearance of the femoral neck and head which Ward's diagram so well foresaw (Fig. 4). However, both diagram and radiograph fail to demonstrate the three-dimensional features of the proximal end of the femur, and for this reason the above descriptions of the calcar femorale and internal weight-bearing system are inadequate.

The femoral neck inclines upon the shaft at an angle of about 127 degrees, ranging normally between 113 and 136 degrees (Humphry 1888). The neck is also set upon the shaft at an angle varying from 38 degrees anteversion to 20 degrees retroversion, but which is usually in the region of 10 degrees anteverision (Kingsley and Olmsted 1948). In the opposite direction the neck itself shows a slight curvature with its convexity directed forwards (Walmsley 1915). This twisting and turning presumably represents the developmental response of the femur to the upright position which demands conversion of the weight-bearing stresses from an oblique to a vertical direction. It also suggests that, in basic outline, the proximal end of the femur is striving towards a spiral form. It is hoped to show that this observation provides the key to a better understanding of the internal weight-bearing system.

By stereo-radiography the calcar femorale and medial trabeculae of the internal weight-bearing system are seen to be an upward and spiral continuation of the postero-medial cortex of the shaft, and the lateral trabeculae an expanded and rotated continuation of the anterolateral cortex. The medial group of trabeculae occupies a postero-inferior and the lateral group an antero-superior position in the femoral neck. This description may be clarified by the following experiment in which a tube of multiple parallel wires is mounted on a wax former to represent the radio-opaque Haversian systems with their concentric lamellae on which the radiological appearance of the femoral shaft depends (Fig. 5). The spiral conformation of the proximal end of the femur suggests that its peculiar angulation has
Figure 1—The posterior aspect of the proximal end of the femur. Figure 2—Frontal section of the upper third of the femur to show preponderance of cortical bone in the shaft and of cancellous bone in the neck and head.

Figure 3—Internal weight-bearing system in the femoral neck. M—medial system of lamellae; L—lateral system of lamellae; W—Ward’s triangle; and I—intertrochanteric arch. Figure 4—Diagram from *Outlines of Human Osteology*, F. O. Ward, 1838, for comparison with radiographic appearances. (Reproduced by permission of the Editor, *Journal of Bone and Joint Surgery*, American volume.)
Figure 5—Radiograph of tube of parallel wires. Note appearance of "cortex" where wires are superimposed. Figure 6—Disposition of wires after twisting tube to show their similarity to the pattern of the medial and lateral lamellae in the internal weight-bearing system.

Figure 7—Horizontally arching disposition of the wires in the antero-lateral half. Figure 8—Vertical disposition of the wires in the postero-medial half.
been achieved developmentally by simple twisting of the original shaft in an inward, forward and then backward direction. Similar twisting of the tube of parallel wires is found, in practice, to produce a radiographic shadow closely resembling the trabecular pattern of the internal weight-bearing system (Fig. 6). Bisection of the wire model in the line of its spiral into antero-lateral and postero-medial halves is then found to present a horizontally arching disposition in the antero-lateral half and a near-vertical disposition of the wires in the postero-medial half (Figs. 7 and 8). Parallel wires have been chosen for the sake of clarity although their use is strictly incorrect, since the Haversian systems oriented along the lines of stress (Benninghoff 1925) are diagonally disposed to the long axis of the femur (Harris and Cohen 1957).

Further examination shows that the third group of trabeculae which decussates with the lateral group in the intertrochanteric region is centred upon a lamellar expansion of the thickened ridge in the femoral cortex known as the anterior intertrochanteric line (Fig. 9). A small area in the anterior wall of the neck, the posterior wall of the neck and the two trochanters with their communicating ridge are seen to be devoid of specialised trabeculae. Ward’s triangle therefore represents a central area where trabecular reinforcement is absent in the medulla and in both anterior and posterior walls of the neck.

The calcar femorale is usually displayed by removal of the posterior cortical shell of the upper femoral metaphysis. This dissection results in partial removal of the calcar itself which then appears as an isolated plate or spur projecting into the metaphysis (Fig. 10). Removal of the cancellous tissue in the femoral neck after bisection of the femur through the lesser
Bisection of the femur through level of lesser trochanter to illustrate true nature of calcar femorale as the uninterrupted continuation of the postero-medial cortex on which the lesser trochanter is based.

Serial radiographs of the calcar femorale showing its laminar structure. Figure 12—Antero-posterior view. Figure 13—Oblique view. Figure 14—Lateral view.
trochanter, however, reveals the calcar as an uninterrupted laminar sheet of almost cortical hardness lying in continuity with the postero-medial cortex and overlain by the lesser trochanter (Fig. 11). The laminar structure of the calcar is demonstrated by serial radiography in different degrees of rotation (Figs. 12 to 14), and by every radiograph of a displaced subcapital fracture of the femur (Fig. 15).

The weight-bearing capacity and therefore the total amount of bone required in the femoral metaphysis need obviously be no greater than in the diaphysis. Expansion of the upper end of the femur has thus been achieved simply by a splitting-off or lamination of the closely packed lamellae of the shaft (Figs. 16 and 17). Hirsch and Brodetti (1956) have shown that the combined cortical and cancellous layers in both superior and inferior aspects of the femoral neck are each responsible for 50 per cent of its weight-bearing capacity, and Tobin (1955) pointed out that, weight for weight, cancellous bone is as strong as cortical bone. Above the level of the lesser trochanter, therefore, compact and cancellous bone have made a compromise—each accepting a share of the load whilst, at the same time, preserving the tubular nature of long bones elsewhere.

This tubular character of the femoral neck is partly concealed, as Bigelow (1900) suggested, by the developmental addition of the trochanteric traction epiphyses. Removal of the trochanteric system en bloc from the anatomical specimen certainly affects but little the radiological pattern of the weight-bearing trabeculae. Furthermore, the mode of attachment of these bulbous trochanters is much in accordance with Bigelow's views. A double-skinned appearance is seen both where the lesser trochanter meets the calcar femorale (Fig. 18) and where the greater trochanter merges with the superior aspect of the neck (Fig. 2).

THE SUB-EPIPHYSIAL ZONE

Microscopic examination of the sub-epiphysial zone shows it to be the meeting place of the medial and lateral elements of the internal weight-bearing system which here approach and fuse with each other for the first time in a series of Gothic arches (Fig. 19). A similar arching arrangement is found at the apex of the intertrochanteric arch, and the circumferential lamellae throughout the entire internal aspect of the diaphysis also terminate in this way (Fig. 20). The above description of the metaphysial lamellae refers only to their appearance in frontal section, and does little to clarify the true nature of their arching disposition. This may be shown by microscopic dissection, however, to represent the cross-section of widely curved bony plates, evenly separated from each other by trabecular tie-beams and merging with their fellows from the opposite cortex in a series of lamellar domes (Triebel 1922). This observation
at once provides a geometric interpretation of these lamellae by which their behaviour may be explained and understood (Fig. 21).

The cancellous patterns of the internal weight-bearing system are therefore formed by wide bony plates or lamellae which, on end section, create the illusion of narrow beam-like structures. The term "trabecula" which has been freely used in describing these cancellous patterns then becomes misleading since this term denotes a small beam. It may justly be applied, however, to the innumerable tie-beams which connect and support the lamellae in the femoral head and neck (Fig. 22). The expression "internal weight-bearing system," which has likewise been used freely, ought not to be held to imply the existence of isolated arrangements of cancellous bone peculiar to the femoral neck, but should be regarded rather as a convenient way to describe the twisted and expanded lamellae in the proximal end of the femur as they are visualised radiologically or on coronal section.

THE EPIPHYSIAL SCAR

During the years of growth the epiphysial plate forms a barrier to the upward extension of the weight-bearing lamellae in the femoral neck. In a young adult femur the site of the epiphysial plate is demarcated by a clearly defined epiphysial scar. It is generally believed that the specialised lamellae of the internal weight-bearing system are then continued upwards through this scar to reach the articular margin of the head, but careful examination shows that this is not so. Neither the medial nor lateral lamellae cross the line of the scar. The medial lamellae are certainly projected into the epiphysial segment of the head, but a well defined breach in continuity may be discerned in each lamella at the level of the scar (Fig. 23), and the lateral group is likewise confined to the sub-epiphysial zone. The epiphysial scar of
early maturity does not persist throughout life but becomes progressively less distinct with advancing years until, in the aged, its remnants are seldom to be seen. The lateral epiphysial arteries run within protective tunnels of lamellar bone in the juxta-epiphysial region, and these tunnels may sometimes be mistaken for the epiphysial scar (Fig. 24).

THE MECHANICAL ASPECTS OF THE FEMORAL NECK

The manner in which the neck of the femur functions as a weight-bearing structure has been the subject of conjecture for many years. Ward (1838) likened the femoral neck to a street-lamp bracket, and Culmann (1866) compared its function to that of a crane. These theories, based upon the appearance of the neck of the femur in frontal section, presume the existence of both compressive and tensile stresses in the internal weight-bearing system. They ignore the fact that, unlike the static forces in wall-bracket or crane, the dynamic strains of weight bearing through the hip joint must form a perpetually changing pattern with every alteration in movement or posture. Furthermore, the femur is not securely anchored to an unyielding base, and its function as a member of the movable linkage supporting and balancing the trunk upon the lower limb is far removed from that of a crane.
The presence of compression forces in the neck of the femur is easy to understand, but the co-existence of tension stresses is not universally accepted. Farkas, Wilson and Hayner (1948) point out that if tensile stresses amounting to two or three hundred pounds were to arise in the upper femoral epiphysis slipping would normally occur since the epiphysial line could hardly withstand such an enormous displacing force.

Some confusion has been caused by the disappearance of the "tensile" lamellae in coxa valga (Fig. 25), and by their increase in coxa vara when they may assume an intensity even exceeding that of the "compression" group (Fig. 26). This variation, however, is not the result of an actual increase or decrease in the number of these lamellae, but depends upon whether they are seen in full-face or profile. In coxa valga they remain in their original position as the circumferential lamellae of the antero-lateral cortex where they are poorly visualised. In coxa vara they expand and rotate to present in profile as clearly defined individual structures. The numerical variation of these lamellae is therefore illusory, and their radiological intensity depends upon the degree of rotation in the femoral neck. Further evidence for this belief is provided by the fact that these so-called tensile lamellae are poorly developed in Neanderthal or Spy men, and are completely absent in primates or quadrupeds (Walkhoff 1904).

The tensile action of the muscles which fix the head of the femur firmly in the acetabulum must be resisted by an equal and opposite compressive force in the femoral neck as a whole. It is difficult, therefore, to accept the presence of two tensile systems in opposition to each other, and if the lateral lamellae of the internal weight-bearing system were indeed to be tensile in nature they would surely buckle as soon as weight bearing was begun. Much thought and argument have been expended by many writers in attempting to clarify this provoking
FIG. 22
Microphotograph to show the trabecular tie-beams or "distance pieces" which separate and support the lamellae in the internal weight-bearing system of the femoral neck.

FIG. 23
Microphotograph of the epiphysial scar in the proximal end of the femur. A breach in continuity may be seen between the medial lamellae of the internal weight-bearing system and their fellows in the epiphysial segment of the head.
FIG. 24
Microphotograph of laminar tunnel which protects and contains the lateral epiphysial blood vessels at the junction of the epiphysial segment of the femoral head with its underlying subepiphysial zone, and which may be mistaken for the epiphysial scar.

FIG. 25
Figure 25—Antero-posterior radiograph showing the absence of "tensile" lamellae in coxa valga.

FIG. 26
Figure 26—Antero-posterior radiograph showing the relative increase in intensity of the "tensile" lamellae in coxa vara.
problem, and the work of Scott (1957), although in a different context, comes at first sight as an attractive compromise. Scott believes that "the subdivision into tension and pressure stresses is somewhat artificial when applied to an elastic substance such as bone." He suggests that the compression and tension lamellae are both subjected to alternating pressure or tension according to whether the bone is under compression or not, and states that when compression is removed a process of recoil takes place and the compression-tension relationship is reversed. This, of course, is true of steel or any other elastic body subjected to strains and stresses within the limits of its elasticity. The point at issue concerns the initiating force, and the weight of evidence indicates that this is mainly compressive in both medial and lateral patterns of the system under discussion. However this may be, the undistorted head and neck of the femur can certainly continue to function as a weight-bearing unit when decalcification has removed all but the medial system of lamellae. The principal thrust of weight bearing is undoubtedly directed through this almost vertical system which retains its integrity long after the lateral lamellae have been sacrificed to age or to disease. Although it would be presumptuous to oversimplify this intricate mechanical problem by denying the presence of all tensile forces in the neck of the femur, the predominance of compressive forces can safely be assumed.

THE MECHANICS OF THE HIP JOINT

The mechanics of the hip joint are usually depicted diagrammatically in the form of a simple lever, but this fails utterly to indicate the complexity of hip joint function, and in its clinical application has led to many fallacious conclusions. The act of balancing on one leg must involve a most delicate co-ordination not only of the muscles around the hip, but of every major muscle in the body. In particular, the function of the hip joint must be intimately concerned with the function of the knee, ankle and foot. Any interpretation of the action of the muscles which bind pelvis, femur and tibia together should thus be related to their primary purpose of supporting and balancing the trunk upon the movable linkage of the lower limb.

It is well established that in the final stage of knee joint extension the femur rotates medially on the tibia as the knee screws home in full extension. This movement will also be reflected at the hip, and simple observation shows that in weight bearing the hip joint also screws home in medial rotation. Just as the neck of the femur has come to acquire a spiral conformity in the upright position, so also have the soft tissues which surround the hip joint acquired a spiral disposition, and muscular contraction about the hip must imply the application of a rotatory thrust to the femur. An element of torsion will therefore be combined with the compressive forces which are brought to bear upon the femoral neck.

If a femur be freely mounted on a vertical axis with its condyles lying in a horizontal plane and downward pressure be applied to the articular surface of the head, the bone will rotate medially (Fig. 27). This suggests that the shape of the femur has been so perfectly evolved that even in the absence of ligamentous or muscular control its inherent response to weight bearing is to screw home in medial rotation, the rise and fall of its spiral compensating for the tilting axis of the knee.

It is well known that the hip joint is locked by the ilio-femoral, pubo-femoral and ischio-femoral ligaments as they are tightened or wound up by medial rotation of the femur, and stability of the extended hip is in this way achieved with the utmost economy of muscular effort. It is less well known that the head of the femur is not perfectly spherical, and lies in congruity with the acetabulum only in the functional position of weight bearing (Walmsley 1928). The hip joint is generally supposed to resemble the artificial ball and socket joint, but examination of the fresh anatomical specimen, from which all muscles and ligaments have been removed, clearly confirms Walmsley's (1928) observation that this allegedly universal joint actually locks in extension and medial rotation, and can be made to unlock by further movement in these directions only at the expense of subluxation. Aeby (1863) described the femoral head as a rotational ellipsoid, but it may more accurately be visualised as a hemisphere.
twisted slightly out of truth articulating with a similarly twisted acetabular runway with which it is congruous only in the position of extension and medial rotation. As Walmsley (1928) stated, the hip is a screw joint.

It thus appears that the femur serves as an independently acting member within its spirally disposed ligamentous and muscular sleeve, and weight bearing at the hip may be regarded as a turn and lock mechanism which depends upon 1) the natural response of the femur to vertical loading by rotating medially, 2) the locking of medial rotation by the peculiar conformity of the articular surfaces, 3) the restriction of medial rotation by the ligaments about the hip, and 4) the overall control of this rotation by the muscular interplay between pelvis, femur and tibia.

**SUMMARY**

Many analyses of the geometric arrangement of trabeculae in the proximal end of the femur have accepted and perpetuated the theories of Ward (1838), Culmann (1866) and Meyer (1867), and have contributed to the belief that the structure of the femoral neck embodies mechanical principles which are foreign to bony formations elsewhere. This isolated departure from the normal pattern of skeletal behaviour is considered to be most unlikely, and an attempt has been made to show that the structure of the femoral head and neck departs but little from the normal anatomy of the long bone.
From a developmental point of view, the proximal end of the human femur is believed, in its simplest interpretation, to represent an upward continuation of the original shaft which has undergone rotation and expansion. The cancellous arrangements of the internal weight-bearing system are likewise believed to represent the expanded and rotated lamellae of the neck as they are presented radiologically or on coronal section.

The forces acting upon the proximal end of the femur are considered to be mainly compressive in nature, and both crane and street-lamp bracket theories have therefore been rejected. The spiral conformity of the proximal end of the femur has been related to the spiral disposition of the soft-tissue structures that surround the hip, and in the interpretation of hip joint mechanics the principle of the screw has been preferred to the principle of the lever.

I wish to thank Dr A. A. Miller and his technical staff for their many courtesies in placing the resources of the Pathological Laboratory at Preston Royal Infirmary at my disposal. I am also indebted to Miss M. G. Work, M.S.R., and her team of radiographers who have so willingly undertaken the innumerable radiographic investigations which this study has entailed.

REFERENCES