The Classic

The Architecture of the Trabecular Bone (Tenth Contribution on the Mechanics of the Human Skeletal Framework)

Georg Hermann von Meyer

Abstract Hermann von Meyer may rightfully be considered the original proposer of the concept of trabecular architecture following patterns suggesting the directions of principle compressive and tensile stresses in a similarly shaped trabecular structure. Until the mid 19th Century, few had observed trabecular architecture, and when depicted was generally considered to have little regularity. In the 1830s Bourget, Ward, and Wyman independently described the regularity of trabecular architecture, but according to Koch (1917) the proposed explanations were in error or overly simplified. Karl Culmann, an engineer and the developer of “graphic statics,” attended a lecture of von Meyer and made the connection, which was then developed by the latter in this seminal paper. We present the paper in translation here. The original German article entitled “Die Architectur der Spongiosa” was often written

in long, cumbersome sentences, with sometimes obscure meanings. We have taken considerable license in translating, rearranging punctuation, and condensing the material into modern terminology and style, while attempting to maintain the flavor of von Meyer’s writing. We thank Dr. Per K. Amundson for the original translation; Drs. John Skedros and Richard Brand made additional suggestions. An accompanying biographical sketch of Hermann von Meyer is available at DOI [10.1007/s11999-011-2040-6](https://doi.org/10.1007/s11999-011-2040-6).

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Trabecular bone¹ generally makes the impression of an irregular accumulation of bony beams and plates which may be thick or thin and in reference to their arrangement are either wide-meshed or close-meshed.

However, certain typical differences in the arrangement and configuration of the trabecular bone can be recognized and therefore I have proposed two primary forms of trabecular bone in my articles on the development of bone (Muller’s Archive, 1849, page 328). These I will designate as real and false. I believe the characteristics of these two forms can be suggested because true trabecular bone arises from the original cartilage of the bone; the false form, on the other hand is

formed from the cortex combined with the inner remodeling.² The reason for this interpretation was the arrangement and location of the occurrence of the two forms in that the presumed false trabecular arrangement was located in immediate proximity of the existing cortex; and characteristically made of parallel lamella connected by small diagonal rods; the most distinguishing characteristic is the continuity with the most recent layers of cortex. On the other hand, the true trabecular bone is composed of thin beams and is round-meshed,³

¹ Editor’s note: von Meyer used the term, “substantia spongiosa” or simply “spongiosa.” This has been replaced throughout with the more modern, “trabecular bone” or where it seemed more general, “cancellous bone.”

² Editor’s note: The writing here is obscure and the author used the term, “substantia dura” which we have interpreted as, “cortex.”

³ Modern micro-computed imaging technology has provided new ways to identify specific morphological characteristics of cancellous bone. For example, the structural model index (SMI) reflects the distribution of trabecular morphologic types that include: (1) rod-like trabeculae, (2) plate-like trabeculae, and (3) relatively very dense

Plate XVIII Original plate XVIII which includes Figs. 1–9

located more in the inner part of the bone, where it gradually changes into the spider web network of bony substance; which at many locations is encased by marrow.

Although I offered reasons for these distinctions, I can through more recent investigations, no longer recognize a distinction, even when this remains essentially correct.

I find that the trabecular arrangement suggests its purpose: such an arrangement of the bony mass allows a larger outer circumference without a large weight. This familiar view of the purpose of the trabecular arrangement is correctly held and is suggested by finding such arrangements at so many locations; on the other hand we must also convince ourselves that through the rarefaction of the bony substance

the strength of the individual bones is relatively high. We determined through more detailed investigation that one sees an apparently well-intended (“wohlmotivirte”) architectural arrangement closely interdependent with the statics and mechanics of the bone and therefore will develop in a given location. The exception is within the larger marrow spaces where they project inward in a delicate filamentous network as if as their support came through marrow. This suggests they are left over from resorbed trabeculae during the development of the bone.

As one investigates the trabecular bone in reference to its arrangement and strength, one finds such trabecular forms arranged for only unidirectional resistance and others capable of multidirectional resistance.

The simplest form and at the same time the primary form of trabecular bone is that which is capable of unidirectional resistance. For example, one finds one this form at the lower end of the tibia. This can be shown in Fig. 3, a schematic representation of a coronal cross-section: from the joint surface rise small plates that are deposited in parallel fashion, rise sideways and gradually converge with the cortex; the outer plates are the shortest, the inner the

Footnote 3 continued

(low porosity) concave plate-like structures that resemble honeycombs, which are also referred to as spherical voids (Hildebrand et al., 1999). Von Meyer appears to describe all of these morphological types. In some instances his description of the most dense “round meshed” trabeculae appear to be consistent with the honeycomb-like morphology. See Hildebrand T, Laib A, Muller R, Dequeker J, Rueggsegger P. Direct three-dimensional morphometric analysis of human cancellous bone: microstructural data from spine, femur, iliac crest, and calcaneus. *J Bone Miner Res* 1999;14:1167–1174.

longest; with the whole appearing as a system of buttresses supporting the cortex. As one notices the form of the cortex more precisely one gains a more comprehensive picture: each of the little plates converges into and shares in the formation of the cortex; one can see how gradually more and more these small plates, which near the middle of the length of the bone gradually thicken, add to the cortex. The cortex thus appears to be a concentration and condensation of trabecular laminae, or if one would rather so interpret it, the trabecular bone appears as a successive delamination of the cortex. It is immediately visually apparent, that by this arrangement through the cortex of the middle aspects of the tibia from proximal the load is distributed over the entire joint surface and that through this the load is delivered to the entire joint surface of the talus. The previously described lamella are however not freestanding, rather they are inter-connected through thin round or flattened rods or beams, which are more or less perpendicular to and connect the lamella. In this way the lamella are fastened together against one another so that each is connected with every other either directly or indirectly and thereby preventing the deformation of a single lamella.

Interposed between two such rows of lamella is a network of rhomboid shaped gaps with rounded off corners; such round-meshed trabecular bone is then, as easily realized, capable of multidirectional resistance. A typical arrangement of this kind is found in the upper end of the tibia some distance below the intermediate eminence (compare Fig. 4⁴).

Round-meshed constructions of this type are large-meshed and supplied with strong beams. Next to this however, one finds another type of round-meshed configuration that possess small spaces and thinner beams; this smaller type is found at all bony locations in directions not subjected to strong loading, but with a need for resistivity in all directions. One finds such regions in the epicondyles of the femur and the medial malleolus of the tibia.

How this arrangement of the lamella of trabecular bone develops is seen best in the talus and the calcaneus, the latter appearance of which first alerted me to this relationship.

In the talus (compare Fig. 1) one can see on a sagittal section from rear to front that two lamellar systems proceed from this joint surface of the dome; one which projects toward the joint surface of the head facing the navicular and the other projecting toward the lower surface that

supports the talus on the body of the calcaneus. At the top, the talus is therefore constructed of multiple rafters.

The stress transmitted through the talus is then transmitted posteriorly to the calcaneus, and the propagation of the latter corresponds to two strong lamellar systems; a posterior system that proceeds in the direction of the calcaneal tuberosity and thence to the ground; and an anterior system that is the joint surface of the cuboid. These two systems have diverged so sharply from one another that a clear triangular gap forms between them underneath the calcaneal sulcus; this gap is almost invariably present. A third lamellar system⁵ that spans from back to front (posterior to anterior) along the undersurface of the calcaneus will be more closely considered later; for now it should be thought of as a rafter-like structure of the calcaneus and a tension band that opposes horizontal stresses.

The front distal lamellar system of the talus is situated in the same direction, in that it penetrates the subchondral bone of head of the talus, continues through the navicular and through the first cuneiform and is transmitted to the first metatarsal, much in the same manner as the opposing stress on the talus is transmitted from the tibia; that is, from the joint surface the lamellar plates proportionately distribute the stress and some gradually converge to form the cortex of the middle portion. Distally the lamellar plates gradually arise again to converge in a characteristically crossed direction into the subchondral bone of the head. One can assume transmission of the stress on the first phalanx through the cortex system and transmission of the pressure on the sesamoid bone to the floor from the emerging upper cortex system. When I presented this material in the late summer 1866 to the Zurich scientific community, Prof. Culmann (developer of graphic statics) brought to our attention that the direction the specified lamellar platelet system in the head of the first metatarsal describe the same lines which the graphic statics designates as compression and tension curves (or more precisely: the lines of the maximum compression and the maximum tension); it is these lines that denote the directions in which the compression and tension resistance against a load and reflect pure concentrated stresses (without impure “shear stresses”). In a sense, the emerging lamellar platelet system from the lower cortex can be viewed as a system of tension elements especially suited to resist the tension and tearing that would be imposed by the opposing stress from the floor; similarly the lamellar platelet system from the upper cortex provides a system of compression elements that reflect the direction of the compressive resistance to the opposing stress from the floor.

⁴ Editors note: This is the first footnote in the original: 1) Similarly one can see on the cuboid (Fig. 9) how the lamellar systems proceed from the proximal and distal joint surfaces; because of the mutual location of these surfaces the trabecular systems must meet at an angle where in the middle part of the cuboid there is a stronger round-meshed trabecular system. We are uncertain of the intended meaning, but perhaps “mutual” refers to equidistant surfaces in the cube-like bone.

⁵ Editors’ Note: While “lamellar system” is a literal translation, we suspect “trabecular plate system” might be a more contemporary way of thinking about the notion.

The previously mentioned (third) system of lamellar plates running parallel with the floor on the lower side of the calcaneus may be considered a key feature. Without a doubt it was placed there as a kind of tension band against the horizontal stress. We find this principle in the architecture of all whole bone combinations⁶ and in the internal structure of individual bones. I can envision a tape measure that make possible the building of an arch (or better: a bowed hanging work) for example in the foot; regarding the latter I refer to a suitable lamellar system in lower end of the tibia oriented anterior to posterior (Figs. 1 and 2), which is maintained as pure as possible by such an interpretation; also the proximal (hollow) surface of the navicular (Fig. 1) shows a similar lamellar system; and not insignificantly, one should view all the connecting rods lying between the individual plates as agents of this principle, because their presence prevent any deformations due to a different direction of an applied force. If we accept that the large lower system of plates of the calcaneus is such a tension band, then the horizontal direction of this system and the interaction with the two other lamellar systems can be explained, although not however the strong divergence that is recognizable both in the proximal and distal part of the system of lamellar plates. For these we find, without contradicting what we have already recognized, the meaning of this system of lamellar plates: a sufficient explanation based on the suggestion⁷ of the meaning of the trabecular patterns in the head of the first metatarsal. Let us imagine namely the opposing pressure of the floor as a force on the tuberosity of the calcaneus: so is it clear, that direction must go in the same paths as that from above to the floor transmitted stress. The previously mentioned system of lamellae from the talus to the calcaneal tuberosity resist the loading from the ground through pressure curves and the tension curves correspond to the posterior divergent lamellae of the lower horizontal system. However, the previous idea is complicated by the attachment of the Achilles tendon; let us consider its attachment somewhere over the middle of the tubercle of the calcaneus in which case it becomes clear that the middle part of the diverging posterior lamellar system directly receives the tension of the Achilles tendon; likewise it also easy to understand, that the separate small system of plates in the top part of the tubercle certain receives the pressure imposed by the lowest part of the Achilles tendon. In a similar fashion the lamellar systems of the anterior process of the calcaneus can be explained. This part of the bone

receives in the distal part the pressure of the head of the talus; and it is therefore easy to see the anterior descending curves as the tension curves and the anterior ascending curves as the corresponding compression curves. We also find in the head of the talus a separate small system of plates, which receives the pressure imposed by the anterior process of the calcaneus. In this way the distal descending system of plates in the anterior process of the calcaneus is better explained if we examine these plates only as a rafter to carry the pressure from the cuboid; this latter in the earlier view is correct insofar as the distal lower portion of the joint surface of the talus supports itself in the calcaneal sulcus.

Let us move up from the foot, which offers so much to observe a regular trabecular architecture, to the lower end the tibia (Figs. 2 and 3) which has an extremely simple relationship; namely there is a successive delamination of the cortex into a system of plates that project in a slightly divergent direction from the axis of the bone, and finally joins from all sides so that the whole lower joint surface of the tibia lies on the cross-section of this lamellar system. A look on the two figures shows that at each cross section along the lower end of the tibia the counter pressure of the talus is spatially distributed with an accumulation of plates that gradually thicken into the cortex of the middle region to diverts the stress on both sides; or, if one imagines the stress from above downward, that the transmitted stress through the flute-shaped cortex of the lower end is distributed evenly over the entire joint surface with help from the described arrangement. There is, however, a difference between the sagittal section (Fig. 2) and the frontal section (Fig. 3); while the sagittal section shows a well known concave configuration of the joint surface with an anterior to posterior lamellar system resisting horizontal shear that runs parallel to the cartilage, the frontal section shows a joint surface approximating a straight line where this anterior to posterior system of plates is not observed. It appears altogether, that such tension bands are ordered preferentially at concave joint surfaces or in the direction of the concave surface, which can be explained since at such surfaces the direction of stress changes more easily and since pressure against the edges will change the direction to create a horizontal shear force if there is no opposing restraint. The malleoli are filled with small meshed trabecular bone of the round-meshed configuration; these may be seen in cross section in Fig. 2, similar to the patterns in the epicondyles of the femur and similarly the medial malleolus of the cross section in Fig. 3 shows the trabeculae can be thicker or thinner, and either more flat or rod-shaped.

From cross-sections of the distal end of the tibia one can also recognize more clearly than at other places an ordinary condition of the system of lamellar plates as they touch the joint surface. A short distance before touching the

⁶ Editor's note: We presume the author refers to the characteristics of the trabecular patterns near the subchondral bone of opposing bones, where one can imagine a certain continuity of the "lines of stress" across the joint surfaces.

⁷ Editor's note: Presumably the suggestion of Prof. Culmann.

subchondral bone under the joint cartilage, the number of plates increases (about doubles), and their appear smaller and shorter plates between the ends of the long and larger plate; their interconnection with the longer and larger plates is mediated then through intermediate plates and connecting beams. Through this arrangement the stress on the joint surface is even more evenly distributed.

At the upper end of the tibia (Fig. 4) are, as you know, two joint surfaces, each of which transmits the load from the corresponding femoral condyles. As mentioned, the stress is recognizably transmitted from both sides as at the lower end of the tibia, to the cortex on both sides. It follows from this, that in addition to a platelet system on each side, which transfers stress from the corresponding joint surface to the cortex of that side, there is yet another platelet system that originates from each joint surface (and specifically from the intermediate eminence) and that intersecting the opposite platelet system emerging from the intermediate eminence, joins the cortex of the opposite side. At the intersection the trabecular bone has a robust construction due to the round-meshed configuration; sometimes the region of this round-meshed arrangement so large that the intersecting system of plates become themselves somewhat indistinct; however, one can still clearly recognize them near the joint surface and the cortex. Both joint surfaces show also the transverse “stretch band” system of lamellar plates, which from both sides intersect underneath the intermediate eminence and partially pass into one another.

The lower end the femur (Fig. 5) shows the same arrangement as the two ends of the tibia, but without the intersection of the internal system of plates because the joint surface of the two condyles more or less have a single hollowed out joint surface and the departure of the plates from the joint surface is typically in a vertical direction. As one would expect, one finds a very strong tension band system in this location. The epicondyles are either filled with small meshed, round-meshed trabecular bone, or they contribute in the construction of the condyles with a transverse system of plates that continue propagating to their surfaces while isolate vertical plates either approach the surface closely or continue by connecting to the main system of plates through the whole epicondyle.

The most beautiful drawing shows the upper end of the femur (Fig. 6) demonstrates a large platelet system corresponding to tension curves passing from the region of joint surface lying under the fovea capitis and also from the lower outer half of the head through the neck and passing into the lateral, and which intersects with a second platelet system corresponding to compression curves that emerge at the level of the lesser trochanter from the cortex of the medial side of the femur and also extends toward the greater trochanter. A third system emerges from the latter

one displaying continuity in an upward extending system of plates that radiates from the internal part of the upper section of the joint surface and transfers the pressure from the pelvis directly to the cortex to the medial side of the femur. The triangular region enclosed by the previously described three systems of lamellar plates can be filled out through continuations of the last two mentioned platelet systems; more frequently it is filled with fine round-meshed trabecular bone or a complete gap. From the outer half of the upper joint surface of the femoral head originates a system of plates which extend toward the middle of the head where they disappear into the last-named vertical system and the large tension curve system of plates. The trochanter seems analogous to the epicondyles, in that it contains either only thin round-meshed trabecular bone, or as in the drawing shows some vertical plates parallel to the surface, and also the plates of compression curve system can extend up to the surface of the trochanter.

In a section through the pelvis (Fig. 7) which passes through the Superficies auricularis (of the ilium) and the upper part of the acetabulum, one can imagine the counter pressure from the femoral head propagated through two platelet systems, one extending to the outer cortex and the other to the inner cortex and the Superficies auricularis. The system of transverse plates is developed exceedingly beautifully near the acetabulum. In the top part of the cross-section appears the round-meshed trabecular bone so that one can recognize compression and tension curves, and the tension curve of the Ligamenta vaga.⁸

I limit myself for now to these observations. It is a subject, which will need still some investigation, until it is settled more or less exhaustingly: namely an important primary question is offered after the evidence⁹; how the static relationships, which arise in the bone, are capable of causing the formation of such previously described configurations; a further important question is how the internal remodeling within the bone occurs, so that in each growth period (which seems to be the case so far I could see up until now) such a configuration is available for load bearing as much as possible. Interesting relationships will be detected through the maldevelopment of bones, for example with rickets; it furthermore, besides the static relationships, the arrangement of the cross-section and the mechanical influences of muscle tension and ligament tension must be taken into consideration for a proper interpretation and correct understanding of the platelet systems.

⁸ Editor's Note: We presume von Meyer was referring to the ilio-femoral ligament.

⁹ Editor's note: von Meyer used the term, “Nachweis” or proof, but we presume von Meyer meant evidence for the trabecular systems since he offered no proof of his explanations.

How much of an influence these latter are, is shown with the example of the hip bone; some platelet systems in the neck of the talus (Fig. 1) are, without a doubt, due to an influence of the tarsal ligament; in the Patella (Fig. 8) we find two systems of plates which are for the most part parallel to the two surfaces, and which are capable with their biconvex arrangement and conjoined platelet system oriented perpendicular to the joint surface propagate the tension of the tendon and at the same time are able to resist at the counter pressure of the femur; and that frequently discussed lower system of tension plates in the calcaneus is also unmistakably a connecting link between the Achilles tendon on the one hand and the calcaneo-cuboid ligament and perhaps also the calcaneo-navicular ligament on the other hand.

Whatever questions still remain to be solved, one can assume that the described arrangements stand in the closest relationship with the mechanical, namely the static meaning of the individual bones. Indirect evidence is provided by the very remarkable circumstance that the bones of the upper extremity, whose static relationship is minor, show similar yet albeit imperfect arrangements as those of the lower extremity.

More directly, however, by looking at these arrangements, one can see the importance they could provide for the function of the bones.

With respect to this importance I have already mentioned that the delamination of the cortex at the articular ends of a bone can only have such an organization of plates so as to disperse the stress pressure in such a way that a most proportionate an even distribution of stress is possible at all points on the joint surface, and thereby at the same time to organize the bone mass so that without an increase of substance they occupy a larger volume and the arrangement allows for larger and stable¹⁰ joint surface.

Not less obvious is the static meaning of the rafter system contained in the talus and calcaneus.

In this regard of particular interest, however, is the occurrence of the compression and tension curves in the arrangement of the bent systems of plates, which we find best expressed in the first metatarsal and upper end of the Femur. With respect to the aforementioned, it is extremely

instructive to compare the drawing of a bent crane represented in Culmann's book, "Graphical Statics," plate 11. One will find an unmistakable resemblance between this drawing and the systems of plates in the upper end of the femur shown in Fig. 6. Still more striking is the similarity of the arrangements of the latter with the presented curves of Fig. 10. This drawing of a modified bent crane was drafted under the supervision of Mr. Prof. Culmann, to approximately imitate the organization of the upper femur and the cross-section of the neck and to assume a similarly broad load as the femoral head receives from the acetabulum.

The drawings also suggest that the entire collection of the compression and tension curves are densely compressed close to the surface and thus provide resistance from the points of load application, where it is more concentrated in the shallow layers. We now find in the described platelet systems a bodily expression for the compression and tension curves presented by the graphical static method and will also find in the cortex the close packing of the latter at the surface; on the other hand we get from the cortex of the middle part of a bone a completely different idea, in that we recognize with the association of the static meaning of the bone the trabecular bone organization of the bony substance as the original and in the cortex we recognize only a close packing of the elements of the trabecular bone.¹¹ This view becomes especially important if at certain places, for example at the upper side of the femoral neck, we see short regions of cortex arising, for example the superior aspect of femoral neck where the tension platelet system converges to form a short section of cortex compared with the tension band system in the lower end of the femur (Fig. 5). With this view it becomes clear for us, why all short bones and the articular extremities or condyles contain trabecular bone and the stronger cortex with the large medullary cavity appears only in the middle part of longer bones.

If we find in the illustrated direction of the platelet systems, in which the mass of a bone resists compression, these systems become an important way to determine the manner in which bone resists loads.

¹⁰ Editor's note: von Meyer used the term, "sicherer" or safer, but we presume he meant more stable.

¹¹ Editor's note. Von Meyer's meaning is somewhat obscure here. He used the term, "Ursprüngliche" which we have translated as "original" but perhaps relates to the earliest development of trabecular bone in the area.