Wolff's Law and Connective Tissue Regulation

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Modern Interdisciplinary Comments on Wolff's Law of Connective Tissue Regulation and Rational Understanding of Common Clinical Problems

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But another factor promises greater mastery of disease than merely recording more facts, to wit: discovering and applying the principles of action underlying health and disease.

H. M. FROST (1979)

Preface

In this book the editor - a clinical physician - and competent authors discuss a richly facetted, modern conception of the understanding of diseases and overload injuries of the supporting and locomotor system and thus of the functional, pathobiological tissue regulation.

Despite the great socio-medical significance of degenerative diseases of bones, joints, disks and tenda (osteoporosis, osteochondrosis, periarthritis, tendinosis) as well as of the enormous economic expenditure for interdisciplinary research in this field, scientific activities and clinical therapy are often confined to mainly symptomatic strategies instead of considering the whole and complex biological structure of reasons. The clinically working physician and the competent fundamental scientist (biochemist, biophysicist, epidemiologic, environmental researcher etc.) are similarly faced with the problem of recognizing and classifying the enormous amount of biochemical, biomechanical and (by now often avoided) electrophysiological literature on connective tissue research. Quite often, the latter has to acquire autodidactically his knowledge on medicine and physiology and that is why the analogy of regulating processes in supporting and locomotor systems as well as regulating processes of muscle, heart, kidney and liver are not that familiar to him than to someone who is listening to medical lectures.

For 15 years the editor has dedicated himself to the necessary bridging of clinical and fundamental research, of biologic theory and experimental test, of entire empirical medicine and highly effective modern symptomatic therapy, of internistic-rheumatologic and surgical-invasive attempts in the orthopaedic subject, of macroscopic-biomechanical and ultrastructural-biochemical level within the medical basic research. And despite manyfold attempts respective representatives still find it difficult to interpret their professional terminology and come to an agreement with the untrained counterpart in clinical and experimental connective tissue research.

In 1987 the editor presented the habilitation "On Pathophysiology of Arthrosis. A Theoretical and Experimental Study with Special Consideration of Bioelectrical

Regulating Mechanisms in Cartilage Matrix" and draw the conception of a new electrophysiological function of native collagenous fibrillae from it. It is interpreted as a piezoelectrical biosensor and "nerve"-analogous electrophysiological signal leading structure between matrix and cell, in cell-to-cell contact as well as between tissue cell and free nerve endings (Bioelectrochemistry and Bioenergetics, 22 (1989) 241-254).

A world famous forefather of functional biological tissue understanding has been found in our own house by a lucky coincidence. Professor Julius Wolff (1832 - 1902), founder of the Orthopaedic Clinic in the Berlin Charité, that well-known medical research establishment of Robert Koch, Rudolf Virchow, Emil du Bois-Reymond and Ferdinand Sauerbruch, has worked for more than 2 decades on clearing up the architecture of bone trabeculae, long time before X-rays have been discovered. Julius Wolff was the first to prove that spongiosa trabeculae are obviously precisely directed in line with biomechanical lines of forces going through the bone. He proved that this architecture might be physically understood (e. g., permanent orthogonal crossing of trabeculae structure) and that this architecture of living bone is always striving to adaptate the actual and functional stress, to basically rebuild after a fracture consolidated in a wrong positioning and to newly adaptate the flow of forces through the respective segment of the body (see symbol on the cover of this book).

In 1892 Julius Wolff published his life's work in the monograph *"The Law of Bone Remodelling"* in the publishing house August Hirschwald Berlin. His main statement that the living bone is able to adaptate to changed stresses, to compensate congenital and posttraumatic wrong positionings and - in a modern sense meaning muscles and heart - to be in a limited manner "trainable" by functional stimuli, is summarized in Wolff's law - today known as a terminus technicus all around the world.

At the beginning of the 80s the editor came across Julius Wolff in American literature on bioelectrics (C.A.L. Bassett) and discovered then the famous monograph of 1892 in the back stack of the clinic library. In March 1986, at the occasion of the 150th birthday of Julius Wolff the editor published an honorable address in the *Zeitschrift für klinische Medizin* (journal on clinical medicine) - in the same year when the publishing house Springer published the English translation of Wolff's monograph. Thereby, in 1988 on behalf of the 100th anniversary of the Orthopaedic Clinic of the Charité he was appointed to organize a symposium that took place from April 4 to 7, 1990, as "International Symposium on Wolff's Law and Orthopaedic Pathophysiology", with Professor Hartmut Zippel being chairman.

The purpose of this meeting of many outstanding clinicians and researchers was to study Wolff's law not only in the sense of an important black-box relation but with all the interdisciplinary natural-scientific and clinical attempts to find a pathophysiological and biocybernetic foundation and a causal biological understanding. This goal was achieved under a very special human and political atmosphere, meaning in a time just after the Berlin Wall had been opened, and scientifically in an unexpectedly creative variety and unusual interdisciplinary completeness.

To this belonged a review of interesting details of medical history as well as the very important statements on aspects of biological scientific theory which make it just possible to get a scientifically exact and biologically competent summary of all the details and facts on this subject. Biomechanical, electrophysiological, biochemic-metabolic and broadfaned clinical items illustrated then the scope of attempts and some new and just little known solution formulations for a rational pathophysiological understanding of tissue regulation.

For economic and conceptional reasons it was unfortunately not possible at that time to have this surprisingly important material quickly and completely published at international level. It is the more pleasant to publish now a selection of statements actualized, reviewed and completed by some additional works to round off this interdisciplinary subject. We heartfully thank the Founder's Association for German Sciences in Essen, and many renowned enterprises in the pharmaceutic and medico-technical industry for their support, as well as the publisher Walter de Gruyter for including this book in its program at short notice und just within Wolff's anniversary in 1992.

It is the desire of the editor to reach both the physician as well as the researcher in the special field of orthopaedics, rheumatology, internal medicine, sports, industrial medicine and accident surgery. Just if each person concerned understands the language and the topic of the other and accepts the biological summary of clinic and research, of theory and experiment as an intellectual challenge instead of creating connective tissue research as a field of parcelled out clans of partial sciences only, one may expect from this research positive impulses for all of the clinical problems concerning therapy conceptions, structural reforms, rehabilitation attempts, health insurance etc., which in our days have to be considered politically and in the medical routine.

Berlin, October 1992 PD Dr. med. G. Regling

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Julius Wolff and the Law of Bone Remodelling

H. Zippel, Berlin

Julius Wolff was undoubtedly one of the most outstanding personalities in nineteenth-century orthopaedics. His work and his influence as well as his significance reach well beyond the historical framework of his time. Not only did he found the "Temporary Outpatient University Clinic for Orthopaedic Surgery" of the then Friedrich-Wilhelm University in 1890; outside of the Berlin area his name is inseparably linked with a long and difficult academic struggle for the development and establishment of an independent department of orthopaedics. His scientific work culminated in the book *The Law of Bone Remodelling* published by the August-Hirschwald Company in Berlin, in 1892, which was an important contribution to the scientific and theoretic fundamentals of the subject.

According to the Science Citation Index, his works are still quoted worldwide nearly 100 times in a given 5-year period in relevant medical publications. In this connection it seems exceedingly remarkable that in 1986, almost 100 years after the first publication of his most important book, the Springer Publishing House published the first English edition of his monograph, translated by P. Maquet and R. Furlong.

Julius Wolff was born in Friedland (Mark Brandenburg) on the 21st of March, 1836. From 1855 to 1860 he studied medicine at Berlin University, and in 1860 he obtained a doctorate in Medicine and Surgery under the guidance of Bernhard von Langenbeck (1810 - 1887) with his work "De artificiale ossium productione in animalibus". He set himself up as an orthopaedist in Berlin. He soon earned the respect and love of this patients who gratefully apostrophized him as "bone-Wolff". (Fig. 1)

In 1861 he qualified as a private lecturer in surgery under von Langenbeck. His lectures, which can be traced up to the summer term of 1869, show his increasing preference for orthopaedic questions of fractures and luxations, of the anatomy and surgery of the extremities.

In 1882 he founded a private orthopaedic institute in the Marienstraße 25 (later named Markthallenstraße D). During the same period, orthopaedic lectures became a basic part of academic surgical instruction. Wolff, who was appointed professor in 1884, offered a whole series of lectures in the years that followed:

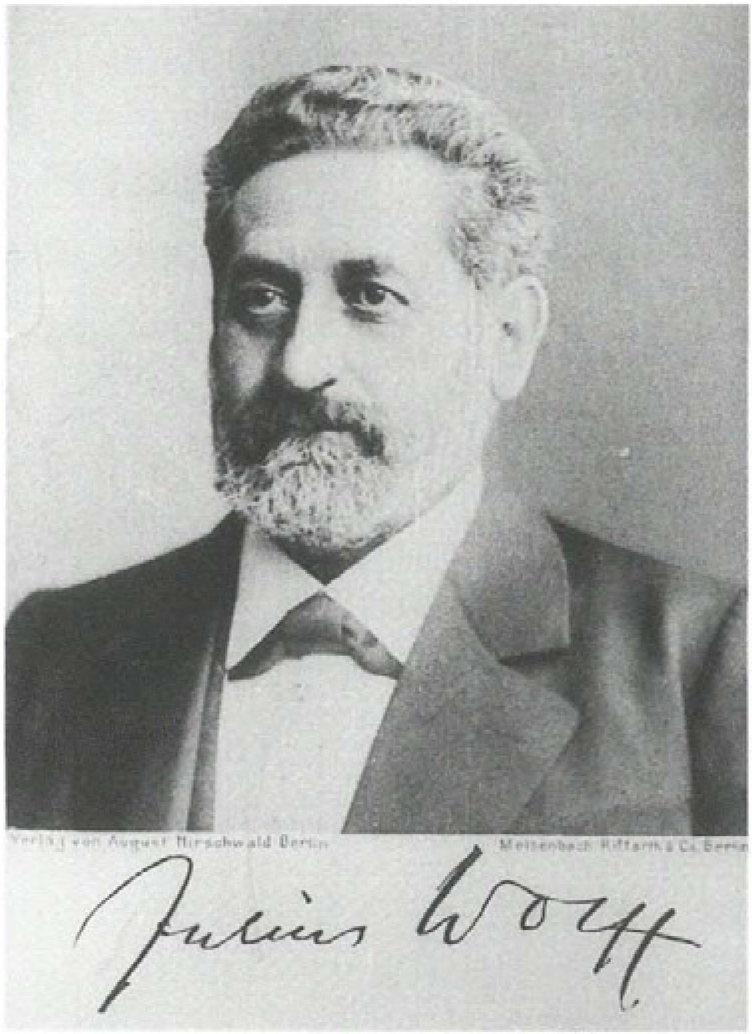


Fig. 1 Julius Wolff (1836 - 1902)

1886 - 1890	"Orthopaedics and Exercises"
1891	"On Functional Orthopaedics"
1892 - 1901	"On Functional Orthopaedics and Practical Exercises" and "Outpatient Clinic for Orthopaedic Surgery and Exercises in Dressing and Operation Methods"

Besides his activity as a lecturer, his endeavors were aimed at the foundation of a university institute of orthopaedics. The then dean and professor of anatomy, von Waldeyer, and all members of the faculty wrote a letter to the Royal Secretary of State, Minister of Ecclesiastical Educational and Medical Affairs, His Excellency Dr. von Gossler, which contained the following:

"The Medical Faculty does not hesitate to respectfully present and support the request by Prof. Wolff to Your Excellency. In the Faculty's opinion, it is entirely advisable to found a special university institute of orthopaedic surgery, particularly since the university here is much frequented, and orthopaedic surgery had developed methods and procedures of its own.

With good reason, orthopaedics may claim the same consideration as the subjects made known by Prof. Wolff (branches of medicine dealing with the eye, ear, nose and throat - the author). *To the Faculty, Prof. Wolff seems to be a suitable person to assume the direction of an institute."*

The faculty having articulated and definitively supported the independence of the new medical branch and the expediency of its institutionalization, the Private Institute of Wolff, situated in Markthallenstraße D (later on the house was named Am Circus 9), was converted into the "Temporary Outpatient Clinic for Orthopaedic Surgery" on May 22, 1890, and Julius Wolff was appointed director and in 1889 Privy Senior Medical Officer (Fig. 2).

Fig. 2 The Wolff Clinic of Orthopaedic Surgery on Markthallenstraße (later: Am Circus 9), as of 1890 "temporary" university institute

Wolff was reimbursed neither for the extensive architectural changes that were carried out in the years that followed by order of the Minister nor for the current expenses of the institute. In the period between 1892 and 1893, repeated requests by Wolff for repayment of costs and a change of the name of the still "temporary" university institute were discussed again and again at altogether six faculty meetings, and finally, at the seventh meeting, they were rejected, despite Rudolf Virchow's (1821 - 1902) objection. Not until the 1st of April, 1894, did the temporary outpatient clinic become a university institute with a budget. On February 18, 1902, Wolff died after a short illness at the age of 66. His last resting place at the Jewish Cemetery in Berlin-Weißensee is intact, but the university institute was razed to the ground during the inferno of World War Two. Wolff's successor as the director of Berlin's outpatient clinic was Mr. Albert Hoffa, by appointment from Würzburg.

In his scientific work Wolff's orientation followed the investigations by Bourgery, Engel, Wyman, and H. von Meyer. He used a steam engine for ivory sawing to cut bones into thin veneer lamellae and analyzed the course of cancellous trabeculae using these preparations. In the mathematical interpretation of the findings he was supported and guided by Prof. Carl Culmann, who was then acting as mathematician at the Zurich Polytechnical School, founded in 1854, and had formerly worked as a railway engineer for the Free State of Baveria.

Culmann was the founder of the so-called graphical statics and had worked earlier with H. von Meyer, whom he had met at a meeting of the Society for Natural Science in Zurich. Comparison of the bone trabeculae of the proximal femur with the construction elements of a freestanding tower crane identified to a large degree the static structures receiving tension and pressure. In 1867, in his first book on the architecture of cancellous trabeculae, H. von Meyer reported on the discovery made by Culmann and thereby he pointed out the basically new mathematical interpretation of osseus structure.

However, von Meyer had neglected to follow up the mathematical analysis of the course of tension and pressure curves in cancellous trabeculae, especially their crossing behavior and their striking on the external surface of the bone. This is where Wolff's real work began. In the period from 1870 to 1871 he tried to prove that as a result of pathological changes of the external form and the static strain caused by some internal or external reasons, there is always a transformation of the inner architecture taking place, directly dependent upon function and according to the mathematical rules of introduction and distribution of forces.

In 1872 he came to the conclusion that the adaptation of an inner structure leads again to secondary changes of the external form, according to mathematically adapted changes of forms by strain, described later by von Roux as a so-called functional external form of the bones.

In 1884 he was able to show, by continuing his investigations, that purely pathological disturbances or changes, i. e., without any primary disturbance of the external form of bones, result in the same mathematically described transformation of internal architecture and external form.

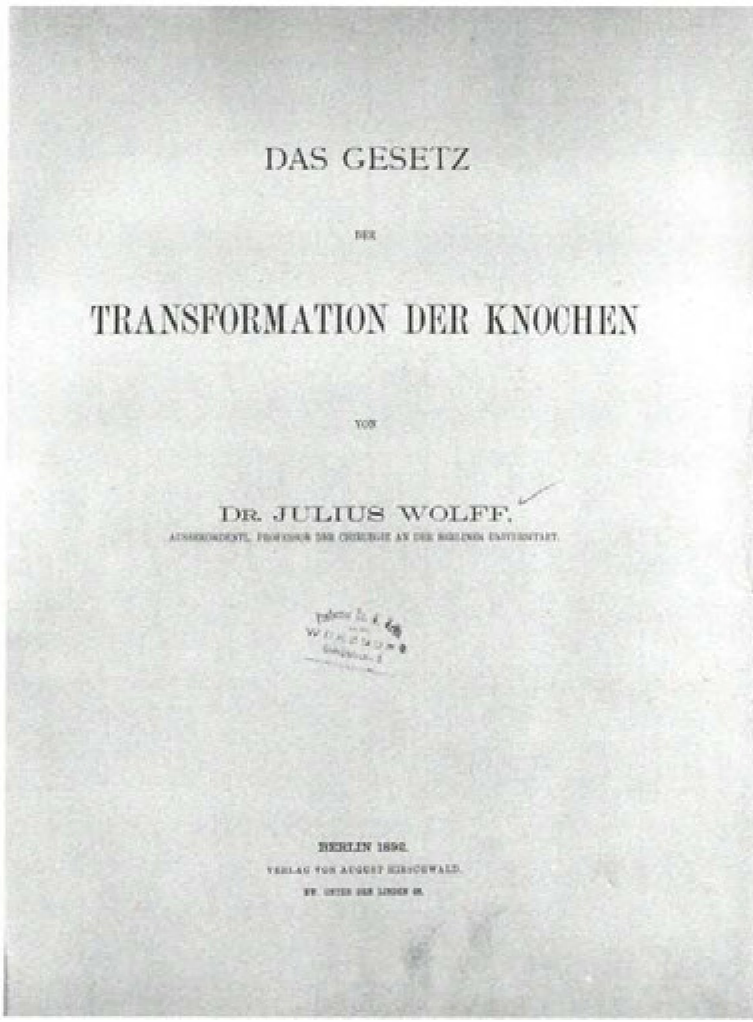
In 1884 - 1885 he finally established proof of the following: Not only does any intentional change of static (functional) strain on the bones change the internal structure and the external form in a pathological way; with the establishment of normal strain the internal and external form of bones can also be returned to normal. Thus, he was obliged to take the terms of the Law of Bone Remodelling in a much broader sense than he had originally in 1870.

"The law of bone remodelling should be understood as that law according to which certain transformations of the internal architecture take place following mathematical rules and as a result of primary changes of form and strain or simply of strain on bones. This applies also to certain changes of the external form of the respective bones following the same mathematical rules" [16].

As early as 1869, Wolff had published the first results of his work on the internal architecture of the cancellous substance of bones in the Zentralblatt für die Medizinische Wissenschaft and in 1870 in Virchow's Archives. As far as his mathematical analysis of tension and pressure trajectories on the proximal femur is concerned, Culmann confirmed in 1869 (in a manuscript of his work; Virchow's Archives, Vol. 50, 1870): *"To your conclusions concerning bones I can add only that you have expressed my inmost thoughts, and I am very glad to read that the structure of bones gives the impression of being such an excellent and rational work of art."*

On April 24, 1884, he presented the first version of the Law of Remodelling of the Internal Architecture of Bones on the occasion of the 22nd meeting of the Physical-Mathematical Class of the Royal Prussian Academy of Sciences in Berlin. In October 1891 this Academy decided to publish all of his research results. On year later, the book was published by the August-Hirschwald-Verlag, Berlin NW, at Unter den Linden 68 (Fig. 3).

If one submits Wolff's complete works to a closer consideration and evaluation, the variety, farsightedness, and topical relevance of his statements are impressive. This impression is the more enduring when one realizes that Wolff began his analyses and investigations almost 30 years before the X-ray was discovered. Friedrich Pauwels [13] reverted to Wolff's interpretation of the architecture of cancellous trabeculae of the proximal femur as oriented to tension and pressure and to the comparison with a freestanding tower crane, made by Wolff and Culmann. Pauwels extended the model of introduction and distribution of powers by ligamentous and muscular principles of stabilization and cerclage (strapping with tension power) and developed it further.



DAS GESETZ

TRANSFORMATION DER KNOCHEN

DR. JULIUS WOLFF.

BERLIN 1892.

Fig. 3 Title page of Wolff's monograph published in 1892

Although Möser and Hein [11] assume of late that in the case of the proximal femur all bones are subject purely to pressure while tension operates via the connected apparatus of muscles and ligaments, Pauwel's model of powers like Wolff's interpretation, which characterizes the possibility of flexion being the norm, is still valid in clinical biomechanics. Wolff's explanation of deformation *"... as an expression of functional adaptation of bone forms for a changed static strain of the deformed part"* [16] i. e., as a deformity of strain as well as the classification and arrangement of various malformations and defects of form of the locomotor system may well be called out-of-date. However, Wolff's finding that an artificial change of strain on deformed parts might cure deformities, since a transformation of the architecture of the bone takes place, laid the basis for the absolutely new, so-called functional orthopaedics. Within his description of the ability of bones to be modeled as a therapeutically usable transformation of power he created the theoretical foundation for and an example of the practical application of redressment. According to Wolff, efficient redressment is confined *"... to overcoming* *the resistance to straitening the deformed limb to the point that the individual segments of the deformed limb have been set in the correct or best possible static relation to each other and to the remaining undeformed parts of the body."* The question is *"first to seek to establish the right function, but to leave the slow formation of the right shape of the bone (in accordance with the right function) entirely up to the transforming power of nature"* [17].

Wolff propagated a step-by-step redressment of congenital talipes, calling it the only reasonable therapy, while *"... a wedge-shaped resection from the foot skeleton and a talus extirpation as well as the open section of soft tissue according to Phelps appear to be unnecessary and even reprehensible surgical interventions."*

For the first time in history, Wolff explained the genesis of internal architecture and external shape of bones as a trophic stimulation of function, with continuous architectural change taking place in the bone, both in the growth stage and in the fully developed stage.

As early as 1872 we find the following statement (Arch. Klin. Chir. Frakturheilung, Vol 14 (1872), p. 301):
"All increases or decreases of bone matrix depends exclusively on the static conditions of the bone. The agent of this relationship of dependence is the striving to maintain function under physiological conditions, i. e., the static fitness of the bone to perform, and the striving to reestablish function under pathological bone flexion."

Thus, Wolff put onto paper what W. Roux was to call the trophic stimulation of function, almost 10 years later (Roux W: *Der Kampf der Teile im Organismus* (The struggle of parts in an organism). Rosenthals Biologisches Zentralblatt, Vol.1 (1881), p. 243). In his hypothesis Wolff even goes so far as to postulate the dependence of all metabolic changes on function.

A comment by Theodor Billroth shows clearly how new and pioneering Wolff's discoveries and ideas were for his time. In a work on the "Final Results of Joint Resection" (Wien Med. Wochenschr. (1871)) he states: *"The only thing I can say about Wolff's work is that I can find nothing with which to disprove his concepts. Just as one has had to get used to the idea that glacial ice flows, one will have to get used to the idea of interstitial or expansion growth of compact bone tissue."*

What was new and directive for the further development, although apparently forgotten for a long period of time, were Wolff's ideas and knowledge about the functional shape of bones. As a result of his research he came to the conclusion that increased pressure not only does not impair bone and make it atrophy; rather it contributes to its formation and development. And even more: that bone tissue needs strain as an essential precondition for its existence.

He writes: "*Wherever pressure and tension stresses are exerted in one and the same bone the development of bone matrix takes place. The strongest development is found at sites of maximal pressure and tension stress, far away from straining points of the stressing and stressed bone, the weakest at sites of minimal pressure and tension stress in close vicinity to these points of contact. But wherever pressure and tension stresses are relieved, i. e., where there is no pressure and tension stress, and where according to graphical statics a shearing stress always appears, bone matrix disappears and resorption gaps, cancellous trabeculae, or new medullary cavities develop.*" [16]. Wolff thereby clearly showed that direct conclusions about strain and stress of bones can be drawn from the architecture of the bone. (Fig. 4)

The special value of Wolff's discoveries lies in their practical application to healing fractures. First he states that callus formation and bone healing occur in phases. Historically new are his statements regarding the first phase - the process of inflammation and filling - the actual callus formation. This procedure, interpreted as a process of apposition and resorptions which can be observed in part also far from the fracture point, represents not an unnatural nor an imperfect principle, but rather, according to Wolff, a most marvelous, highly expedient development, purely in the service of function. The second phase consists of the actual transformation process, the remodelling of the bone, the intensity and extent of which depends on the trophic stimulus of function: This was another of Wolff's historic new discoveries. The latter processes is also known as that of secondary shape transformation, and it explains some long unsettled questions: for instance, why poorly reduced or dislocated fractures heal slower or less well than well-reduced ones. (Fig. 5)

Wolff's works contain experience and answers to fundamental problems in the field of bone fracture healing which in part after manifold historical detours, reappear with due perfection and exact scientific classification in the modern principles and recommendations made by the Swiss Working Group on Problems of Osteosynthesis. Wolff himself called attention to the necessity of follow-up research on fracture healing, especially histological research. Many other problems also reflect the actuality of his work. Wolff's proof that function is a shape-giving principle in bone remodelling led to a continuing search for a system to control bone remodelling and thus bone reformation. In Japan Yasuda [18, 19] was the first to furnish evidence of the electrical phenomena of bones and to describe piezoelectrical or, today, electrokinetic, bioelectrical potentials,which change their polarity in dependence on tension and pressure. Bassett [1, 2] developed the theory that bone weakens at the positively charged side of tension and strengthens at the negatively charged side of pressure, thus adapting the static to the strain. Friedenberg and Brighton [7] discovered negative potentials at fractures. Janssen and co-workers [9] developed from this a theory of physiological effects of electrical potentials with fractures, based on a depolarization in the fracture region.

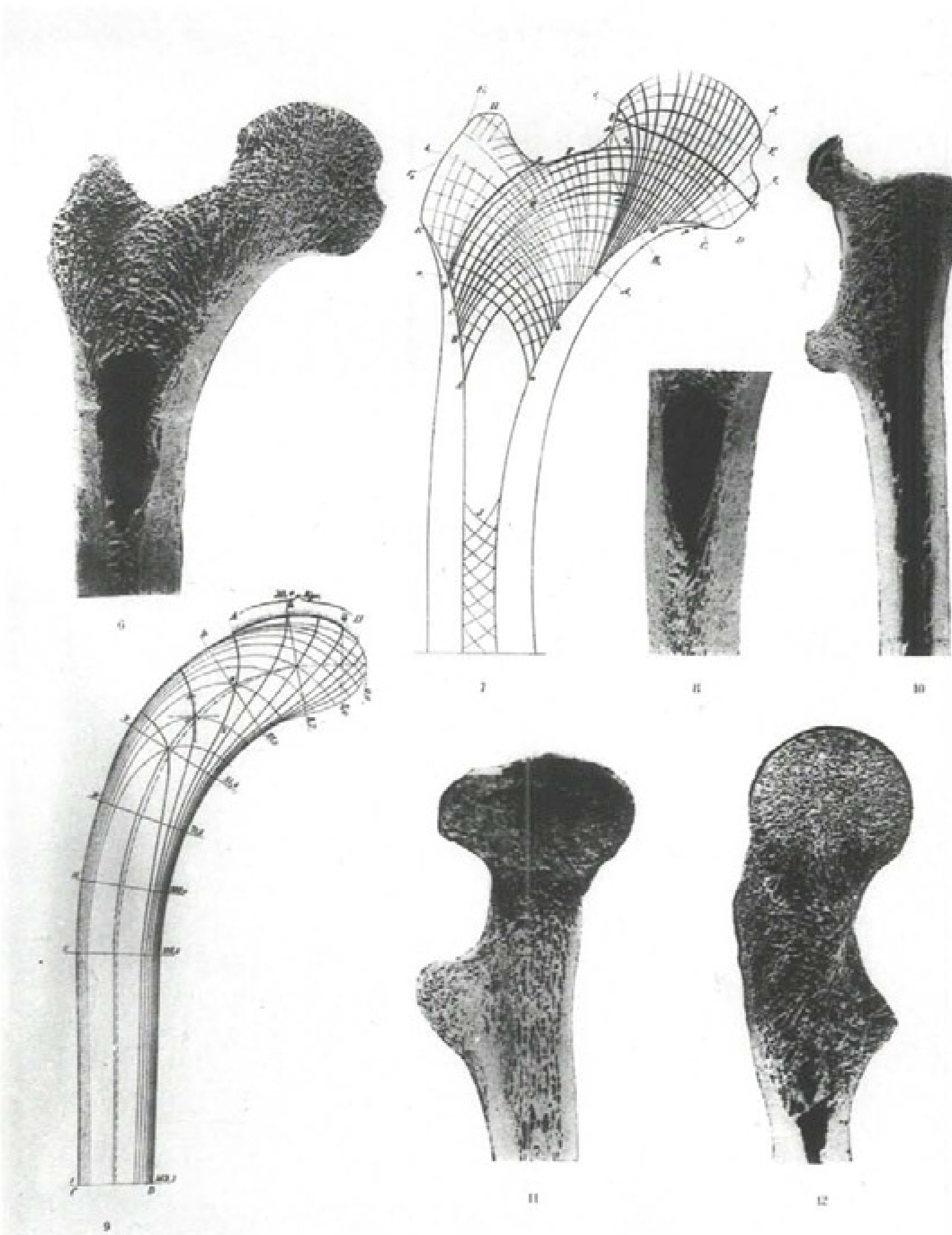


Fig. 4 Figure plate from Wolff's monograph (1892)
Above: veneer section of a proximal femur and reconstruction of the cancellous architecture (orthogonal points of intersection); below: simplified graphical analysis of a proximal femur (without trochanter) by C. Culmann; to the right: arch-shaped veneer section through the so-called neutral plane of the femur.

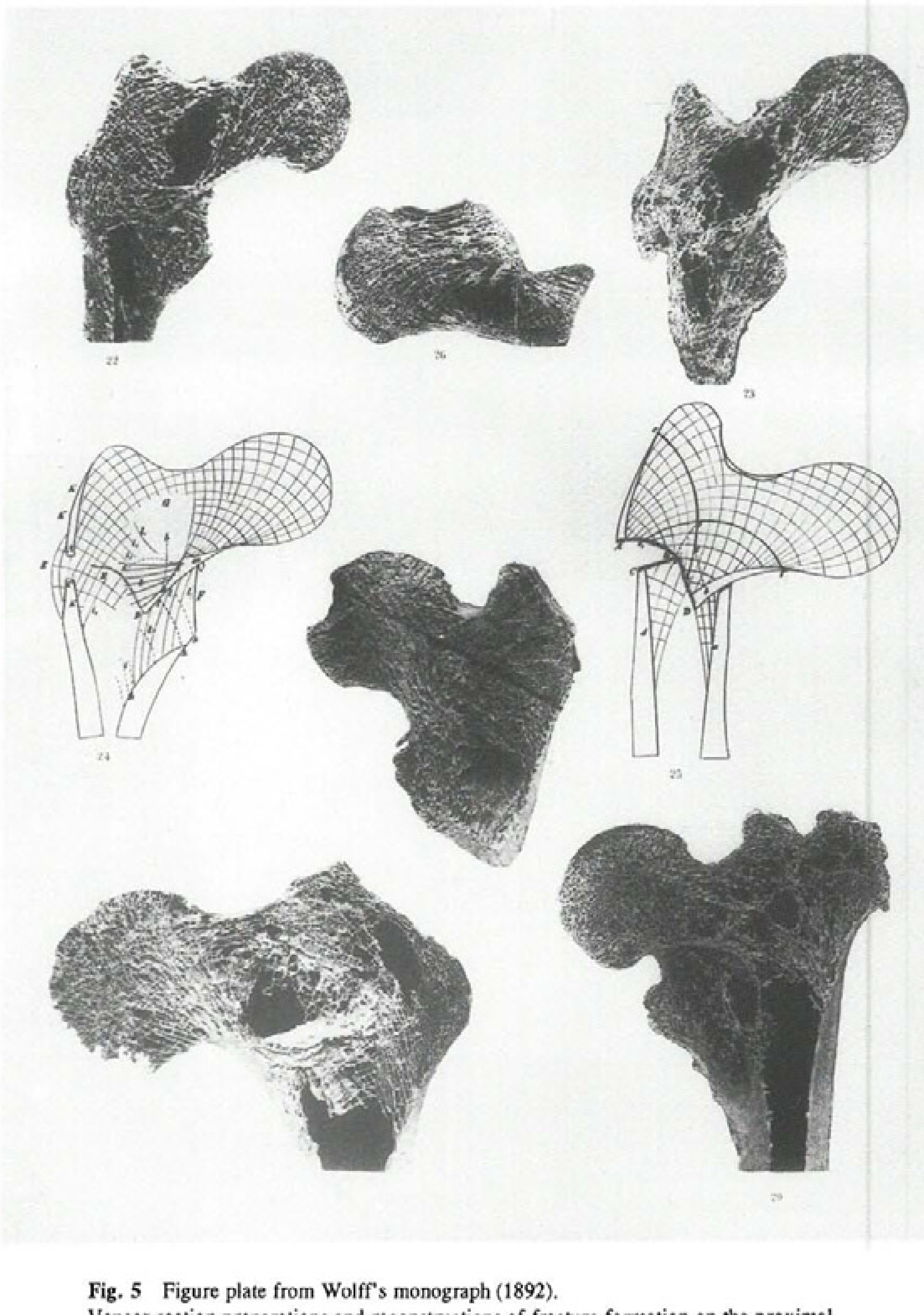


Fig. 5 Figure plate from Wolff's monograph (1892).
Veneer section preparations and reconstructions of fracture formation on the proximal femur and calcaneus.

To date, the exact working mechanism of electrical potentials is not yet clearly recognized and proven. The theoretical considerations begin with changed O_2 pressure and a shift of pH [5, 6, 8] include membrane effects at the cell wall [10, 14] and continue up to direct and central control systems for all reparative processes of the body [3, 4] (Bassett 1984). *The Law of Bone Remodelling* described by Wolff offers starting points for theoretical considerations and pathological interpretations to be applied to other reconstructive and remodelling processes in bone. As examples we may mention the osseous position reactions on materials used for osteosynthesis and permanent implants, osteonecrosis and osteopathy, and the degenerative diseases of the support and locomotor systems, but there are many more.

Of particular importance for an appreciation of his scientific accomplishments is the point made by Julius Wolff himself, with reference to Roux and his "Contributions on the Morphology of Functional Adaptation", concerning the principal validity of his Law for other organs and tissues. If we apply the concept of functional strain as a shape-giving principle, especially to connective tissue and the musculature, the theoretical value of his works becomes convincingly clear.

With apparent but qualified reference to the postural and locomotor system, Julius Wolff thus touched on a key problem of current research on connective tissue, one which in the future as well, will be of topical interest in its scientific and theoretical application.

Julius Wolff was one of the outstanding orthopaedists of the nineteenth century. He was a pioneer and avant-gardist in his field although his name is not connected with new methods of operation or therapy and he did not develop any alternative therapeutic strategies. Rather, Julius Wolff was a person, like many before, during and after his time, who came from the field of surgery, founded and further developed the field of orthopaedics as an independent medical and scientific discipline, and, despite manifold problems, caused by prevailing circumstances, established it as an institution.

His scientific work on the remodelling of bones laid the scientific and theoretical foundation for our field which is of topical interest for research and clinical treatment and which serves as a model for research in the field of connective tissue today.

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A Noteworthy Meeting of the Society for Nature Research in Zurich

Two Important Precursors of Julius Wolff: Carl Culmann and Hermann von Meyer

B. Rüttimann, Zurich

The meeting of two important scientists with very different areas of study led to the confirmation and extension of findings that established not a final, but a sustainable, basis for later research on the structure and function of bone.

The Meeting

In 1866, during the proceedings of the Society for Nature Research in Zurich, professor of anatomy Hermann Meyer, delivered a lecture "On the significance of bones as machine parts and the structure of cancellous bones." Unfortunately, the minutes of the meeting are missing - only the titles of the lectures are listed in the proceedings on the Swiss Society for Nature Research [19] - but everything points to the fact that the meeting took place in summer, probably at the end of July, 1866. One year later the lecture was published as the "Tenth contribution on the mechanics of the human skeleton" under the title "The architecture of cancellous trabeculae" [10].

Present at the meeting, among many other scientists, were Carl Culmann, a very "active" member of the society and prominent representative of engineering science, and - fortunately for us - Adolf Fick (1829 - 1901), formerly prosector and now professor of psychology in Zurich; 2 years later he was called to Würzburg. Adolf Fick reported the course of the meeting to his son Rudolf, who put the recollection of this memorable occasion in writing, first in an annotation to his "Handbook of Anatomy and the Mechanics of Joints" in 1910 [4] and then, in 1928, in the opening address to the 37th meeting of the Society of Anatomy in Frankfurt [5]. A brief section is worthy of citation here:

At the meeting mentioned he (H. Meyer) lectured on the structure of the heel bone, but he also cited the neck of the femur as an example of the mechanical significance of the order of osseus trabeculae. He drew a crane similar to the shape of the upper end of the femur and asked ... Culmann to draw in the tension and pressure lines to be *calculated by him for this purpose, having already drawn trabeculae that were significant - in his opinion - on another piece of paper. Culmann had one of his pupils, Dr. Hedenauer, make the calculation and drawing and, just imagine, it corresponded with the one of H. Meyer. From then on, Culmann cited the skeletal structure as proof of the correctness of his calculations.* The above-named assistant was not Dr. Hedenauer, but Dr. Andreas Rudolf Harlacher (1842-1890), who was assistant to the Swiss College of Technology from 1866 to 1869 and then professor at the Prague College of Technology [17].

The published lecture by Hermann von Meyer mentioned above is illustrated with proper graphics. The original legend to Figure 1 reads as follows: *"This graphic gives a modification of the curved crane that Prof. Culmann had designed under his control with the intention of approximately imitating the shape of the upper end of the femur and the transverse section of the neck and presuming the same wide strain as the head of the femur receives from the socket"* [10].

In 1867, when this work was published, Hermann von Meyer proved to be farsighted when he commented: *"Another important question is how the internal metamorphosis in the bone takes place, such that the form is best fit for service in every stage of growth (as far as I have seen to date, this is the case); interesting relationships will also be found in cases of bone deformities, e. g., caused by rickets etc."*
An answer to this question was provided by Julius Wolff in his book *The Law of Bone Remodelling* [20] in 1892, the year of Hermann von Meyer's death. The first chapter of the magnificent volume contains some preliminary historical remarks, mentioning some precursors of Meyer and the above-described meeting of Culmann and Meyer. Wolff continues: "My own research ... " - mainly the two works "On the Significance of the Architecture of Cancellous Trabecular Substance" (1869) and "On the Internal Architecture of Bones" (1870) - " ... follows directly from the great findings of Culmann." They go on to "The Remodelling of the Internal Architecture" and finally to a formulation of the Law of Bone Remodelling [13]. Wolff is clearly praising Culmann's merits, as he does often in his written works, "but, with reference to our knowledge about the relationships of the internal architecture of bones, great merit indeed is due to Hermann von Meyer ..." [20]. Wolff criticized with good reason - also in the opinion of Hermann von Meyer in his "Statics and Mechanics of the Human Skeleton" [11] - the fact, that the always right-angled crossing of bone trabeculae and the right-angled striking of trabecular ends on the external surface of bones had not yet been clarified and drawn.

Adolf Fick and his son Rudolf emphasized Meyer's findings, not without taking a few shots at Wolff. There is no point today in searching for the reasons for such complaints, based as they are on manifold circumstances now forgotten by history. Rather, both Culmann and Meyer are worthy of renewed interest. They do not cast any shadow on Wolff's memory - far from it!

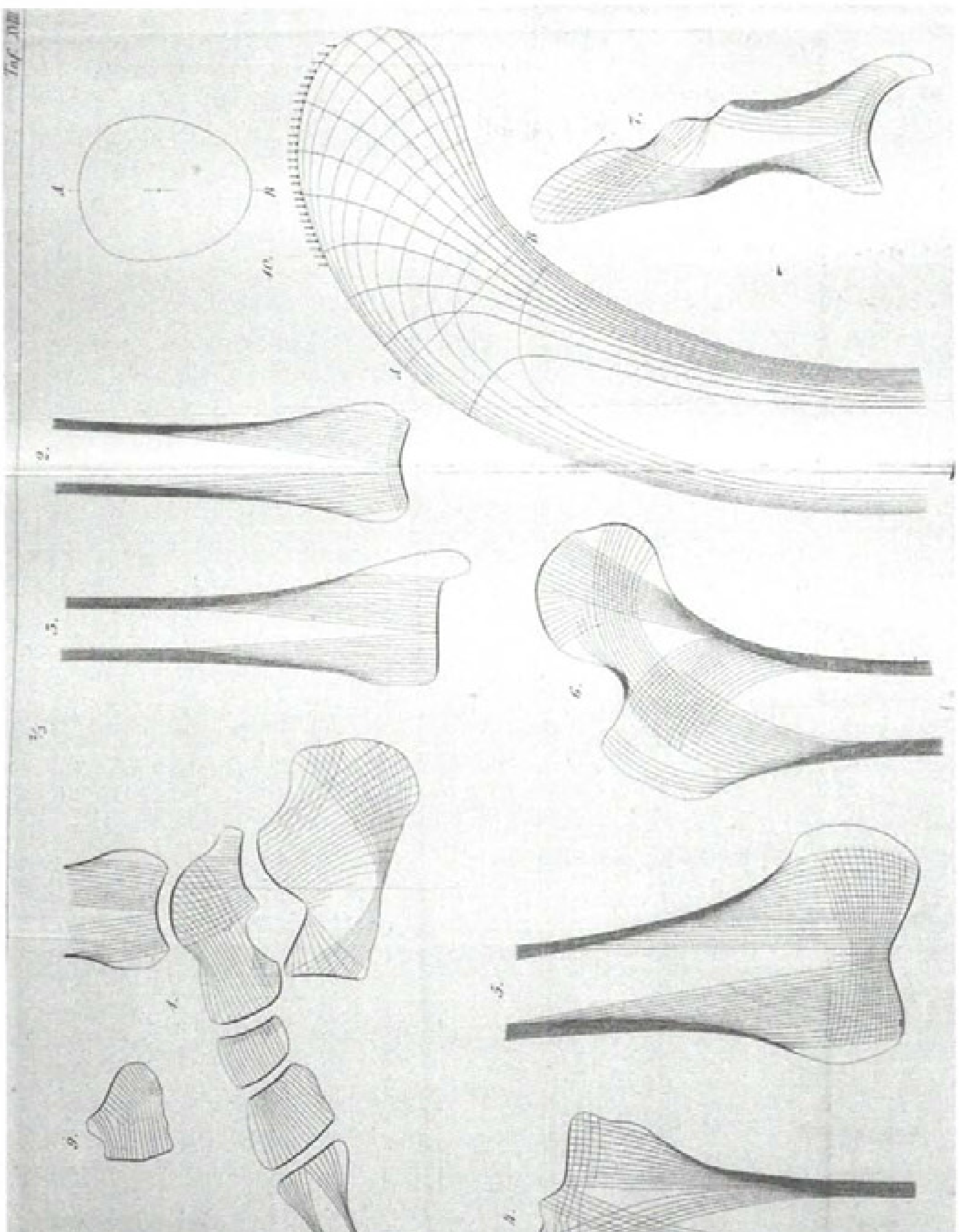

Fig. 1 Illustrations from the published lecture of Hermann von Meyer

Carl Culmann (1821 - 1881)

We find the following passage in a commemorative publication: *"Culmann was talked about enthusiastically, even by those of his pupils who did not understand him. His inexhaustible wealth of ideas, his original way of putting things, his precipitate temperament kept the audience in lasting excitement. There was no lack of amusing moments, e. g., when he suggested the strain on a bridge by the smoke of a locomotive, or when he threw the chalk to the ceiling of the lecture hall to demonstrate the infinite distance of a point on a straight line"* [3].
He constantly strove to adapt theory to practice. *"I can do not better to satisfy this striving than to teach at Zurich"* [14]. According to Tetmajer, his studies always had "a concrete final purpose". Culmann had little sympathy with the morbid writing mania of his time and neglected to document the origin and precedence of many a brainchild" [17]. In all biographical documents he is presented as a kind, personally engaged, benevolent, and modest scholar [6, 14, 15].

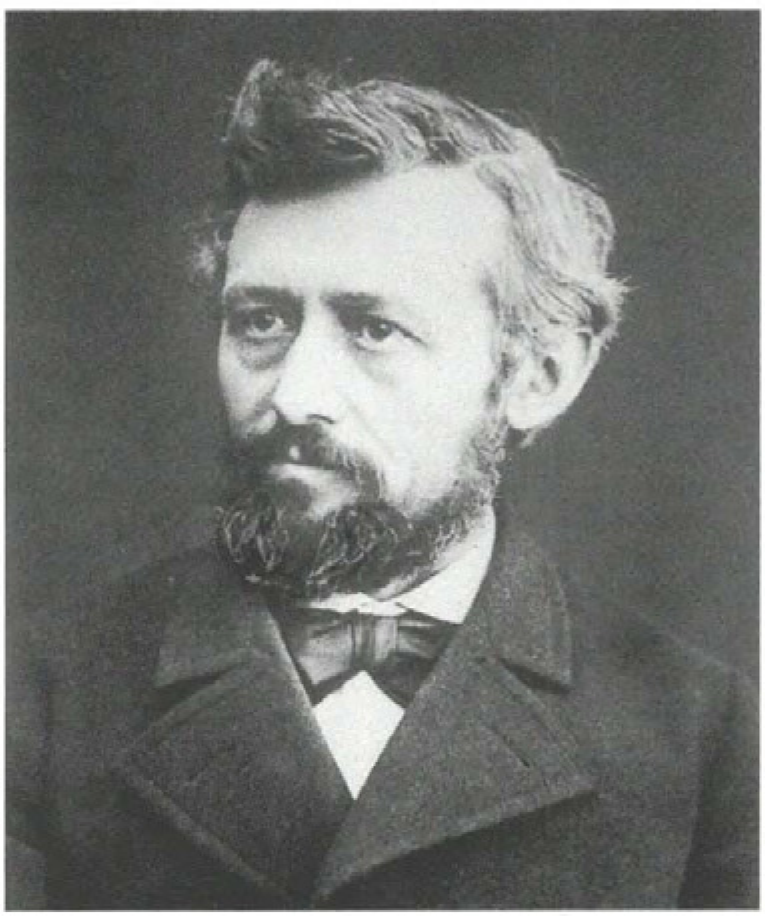

Fig. 2 Carl Culmann (1821 - 1881)

Culmann was born in the Bavarian Palatinate in 1821. He attended college in Weissenburg, Alsace, and - as preparation for the Polytechnical School of Paris - the artillery school at Metz. There he contracted typhus; he took this disease as a sign that God had intended him for Germany. In 1841 he concluded his engineering studies at the Karlsruhe Polytechnical School and became an engineer with the Bavarian State, first in Hof, laying a railway through the Fichtel Gebirge, and later in Munich. A 2-year study trip took him to England, Ireland, and the United States of America. The account of that journey, "The construction of wooden and iron bridges in England and Northern America," received great notice.

In 1855 the school inspector of the newly founded Swiss Polytechnical School succeeded "through fast action in obtaining Culmann's acceptance, and in taking this genius away from Karlsruhe, which also coveted his acceptance" [16]. He became professor of engineering; Cousinery, Poncelet, Möbius, Oudry, Varignon, Poinsot, Clapeyron, Navier, Cletsch and Winkler contributed important ideas to his research. He aspired to make "the art of drawing the language of the engineer in the full sense of the word" [17].

In 1866 his main work appeared, entitled *Graphical Statics* [2]. It is incontestably a personal and epoch-making work. His system was not conceived as strict and unchangeable; it created the opportunity for engineering science to record geometrically the active forces in structures and thus to solve the calculations that arose graphically. The book met with enthusiastic response, was translated, and quickly circulated. Culmann's teachings were continued by Wilhelm Ritter, Luigi Cremona, Otto Mohr, and Heinrich Müller-Breslau. Supplementation and extension of the graphic method by analytical and mathematical processes proved to be necessary [16, 18]. A second, newly adapted edition of *Graphical Statics* was published together with the first volume in 1875 [1], and the second volume in the form of manuscript parts and sketches is found in the library of the Swiss college of Technology.

In 1881, Carl Culmann made a journey to Constantinople; on the way back he fell ill with a lung infection and died in Zurich on December 9.

Georg Hermann von Meyer (1815 - 1892)

Von Meyer was born in Frankfurt/Main as grandnephew of the mayor, who was call "Bible Meyer"; he was also related to the famous paleontologist, Christian Erich Hermann von Meyer (Figs. 3, 4).

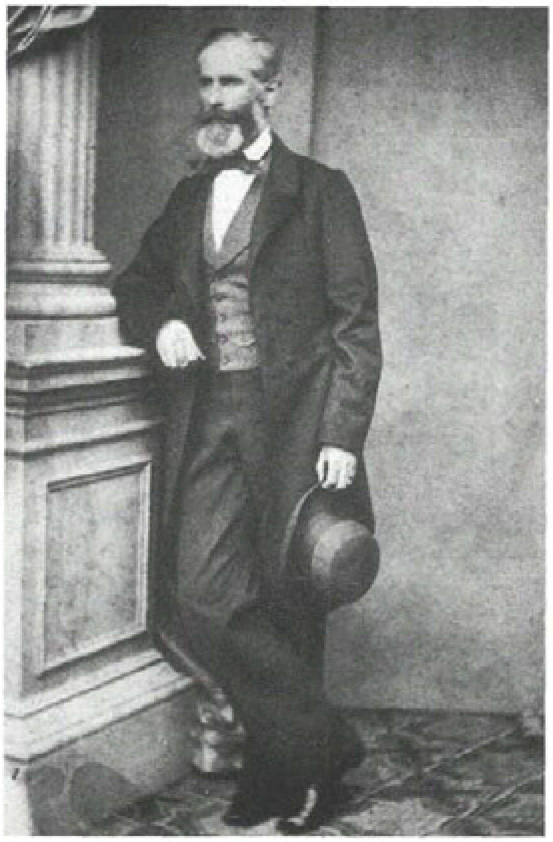

Fig. 3 Hermann von Meyer (1815 - 1892)

Fig. 4 Announcement of a gala on the 50th anniversary of Meyer's receiving his doctorate

He completed his premedical studies in Heidelberg. In 1836 he came as a "foreigner" and "Frankfurter" to the Berlin Clinic, where his promise not to practice later in Prussia was made a condition for him to pass the preliminary examination. In 1837 he received his doctorate, also in Berlin, under Johannes Müller with a dissertation on the muscles in the excretory glandular ducts, written in Latin. Three years later he qualified as a lecturer in histology and physiology at Tübingen. In 1844 he became a prosector under Josef Engel, from 1849 on under Carl Ludwig, at the Institute of Anatomy in Zurich. In 1856 he was offered the chair of anatomy and the position of director of the Institute of Anatomy. He became the dean of the medical faculty and rector of the university. In 1875 he was awarded the Tiedemann Prize by the Senckenberg Society for Natural Science. In the same year, the city of Zurich gave him honorary citizenship, and he was dubbed a knight of the Royal Prussian Order of the Crown, fourth class, with the red cross; later he received the Order of the Crown, third class.

In 1889 (at the age of 74!) he voluntarily resigned from lecturing. He spent the last years of his life in Frankfurt, where he died of severe influenza in 1892 [7].

Meyer's scientific work covered the fields of physiology, histology, anatomy, and pathological anatomy. He considered anatomy by no means a finished science; it was a real concern to him to "work towards the understanding of forms" and to "base himself on physiology, to recognize the body as a complex of physiological apparatuses and to deduce the understanding of forms from the functional meaning of single parts" [8]. His two most important works are the "Textbook on the Physiological Anatomy of the Human Being" and of course the "Statics and Mechanics of the Human Skeleton" [8, 11]. In addition, he produced many papers for the lay reader and is was Hermann von Meyer who introduced the use of colored chalk in lectures on anatomy [9].

Generally known as "Bone Meyer", in 1871 he appeared to Franziska Tiburtius as an elderly man, German, very dignified - in every regard what the English would call "a real gentleman" [7].

A "Very Lucky Coincidence"

This is just how Wolff termed the encounter of Hermann von Meyer and Carl Culmann at the above-mentioned meeting of the Zurich Society for Natural Science. Was it a coincidence that two German scientists met in Zurich of all places? Actually not, since there were a large number of German scientists at the new university (1833) and at the just-founded Zurich Polytechnical School. There were various, mostly political, reasons for young academics and lecturers to go to Zurich. The deciding point for Culmann was the great amount of academic freedom.

Was it a coincidence that representatives of different educational establishments and of very varied branches of study met? Coincidence certainly, played a role here, and such a meeting would be very unlikely in our time. Today, it is difficult to have a clear view of all the meetings and special occasions offered; the idea of "Universitas" - scholarship with overlapping of subjects - is quickly disappearing.

Speaking of "coincidence" reminds me of Louis Pasteur: In 1854, in his inaugural speech as dean of the faculty of natural sciences in Lille, he implored: "Le hasard ne favorise que des esprits préparés"[12] - "Chance favors only prepared minds."

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Julius Wolff and Friedrich Pauwels

Wolff's Concept of a Causal Therapy of Orthopaedic Diseases Using Biological Adaptation Phenomena and Its Realization by Friedrich Pauwels

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At the end of the past century an observation made by Julius Wolff during his extensive osteological investigations became known as *"Law of Bone Remodelling"* (Wolff 1870). Wolff noted that the structure of cancellous bone changes in a certain way and with foreseeable regularity when the mechanical stress on bones changes. He interpreted these changes as processes of adaptation to the new function. In the years 1870-1872 and in 1892 he elaborated a theory which in retrospect may be regarded as the beginning of deliberately functionally oriented orthopaedics. Thus he defined the *"Law of Bone Remodelling"* as

> *... the law according to which alterations of the internal architecture clearly observed and following mathematical rules, as well as secondary alterations of the external form of the bones following the same ruled, occur as a consequence of primary changes in the shape and stressing or in the stressing of the bones (Wolff 1892)*

Julius Wolff (1836-1902) set about his osteological studies at the beginning of this medical career. Induced by the surgeon Bernhard von Langenbeck, he wrote his thesis *"De artificiale ossium productione in animalibus"* (1860). During the following 40 years as a practicing orthopaedist and from 1890 as head of the newly established orthopaedic clinic of the University of Berlin, Julius Wolff never ceased continuing his scientific work on the structure and growth of bones.

A long time before Julius Wolff, the English anatomist John Hunter (1728-1793) had already realized that bone tissue was by no means the stiff, firmly set structure it had been thought to be. Hunter rather postulated that in the course of an individual life bone is subject to continuous remodelling processes as well of reconstructive as reductive nature. In 1842 the Frenchman Marie Jean Pierre Flourens (1794-1867) advanced the same hypothesis. According to Flourens, the growth of long bone only takes place at the surface, i. e., by apposition of new bone substance at the diaphyses and epiphyses and by simultaneous resorption from the wall of the medullary cavity.

In 1860, when Wolff began his osteological studies, this idea still accorded to generally accepted anatomical precepts. Nevertheless some objections were already being raised by several prominent physicians and scientists: In particular, du Hamel, Johannes Müller, Rudolf Virchow, Albert Hueter, and Richard von Volkmann pleaded for the existence of interstitial bone growth. In 1862, von Volkmann supposed that bone changes its internal architecture by means of interstitial growth, the trabeculae realigning themselves. Von Volkmann accorded to mechanical stress a decisive influence on the external shaping of bone. He assumed that compression hinders bone growth, while decompression stimulated it (for review see Krukenberg 1930). This so-called compression theory formed the basis of the concept of stress deformity which was subsequently developed by Hueter and von Volkmann.

> *Stress deformities are those essentially mechanical affections where the deficient confirmation of joint endings and the resulting abnormal situation and direction of the limbs connected in the joint, is the original and main disorder (Hackenbroch 1981).*

Like von Volkmann, Julius Wolff stressed the vital forces of the bone. Thus, he was in opposition to the "theory of passivity" - still commonly accepted in spite of John Hunter's findings - according to which bone was a tissue stiffened in cretaceous formation which no longer changed its form actively, but only through mechanical effects such as abrasion. In his early works Wolff declared himself a supporter of the idea of expansive (interstitial) growth. Although he at first categorically rejected the idea of appositional bone growth, he later came to the conclusion that bone growth might be possible via deposition of bone substance below the periosteum, though the osteogenic power of the periosteum was low - in growing as well as in adult bone. Nevertheless, Wolff resolutely fought the compression theory advanced by von Volkmann and Hueter. In doing so, he was supported by the findings of the anatomist Hermann von Meyer and the engineer Karl Culmann. Von Meyer (1867) recognized in the apparently irregular structure of the substantia spongiosa which repeated itself in corresponding bone in a typical way, a *"well-motivated architecture"*, which had the effect that *"... the stability of the single bones is guaranteed to a high degree."* Using the methods of graphic statics, the engineer Karl Culmann showed that the trabecular lines described by von Meyer followed exactly the direction a technician would demand to achieve an optimal stability with the lowest possible expenditure of material. At places of high mechanical stressing - whether compressive or tensile - osseous apposition is seen, but not the rarefaction that would have been expected according to the theory of von Volkmann and Hueter. Culmann and von Meyer did not go beyond descriptive explanations. The first to draw conclusions from their observations were the Breslauan anatomist Wilhelm Roux and Julius Wolff.

Intensive study of literature and above all innumerable tests carried out on slides of bony veneer convinced Wolff that the architecture of the substantia spongiosa is closely