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The birth of a new scientific field – biomechanics of the skeleton. Julius Wolff and his work "Das Gesetz der Transformation der Knochen"

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A brief biography of Julius Wolff is presented. It is demonstrated that the basis for the law he discovered is the graphic statics method of Karl Culmann and anatomist G.H. von Meyer's data on the internal structure of the proximal femur. It was namely this cooperation between anatomist and engineer that led to the emergence of a new scientific field – the biomechanics of the skeleton. Wolff's errors in biological concepts are reviewed – first of all, the claim that trabeculae always intersect perpendicular to each other. In fact, Wolff limited his concept of the ideal situation in which the mechanical environment is characterized by a sole or predominant load. Also presented is contemporary geneticists' criticism of Wolff's assertions, which arose due to the popularization of the reverse hypothesis – that the shape of the bone can be used to reconstruct actions that "produced" this form according to "mathematical laws". The paper stresses that Wolff's merit lies in his creation of a theoretical concept, which to date is the basis of the development of not only theoretical but also practical adaptation aspects of biomechanics of the skeleton. It is also noted that this concept is, in fact, a model that has all the advantages and disadvantages inherent in the modeling of biological objects.
The Russian translation of the first fragment of Wolff's monograph *Das Gesetz der Transformation der Knochen* (Berlin, 1892) is presented. The introduction into the Russian language of a first-hand source will allow specialists interested in the problems of biomechanics to receive a complete picture of the impact of Wolff's law on the development of modern biomechanics of the skeleton and its significance for the development of orthopedics and traumatology.

Keywords: *Julius Wolff, biomechanics of the skeleton, bone mechanical properties, Wolff's law, lines of force, spongy bone*

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In publications on bone adaptation to mechanical stress, both Russian and foreign authors often cite Wolff's law, which they call "the law of bone remodeling" [1–9]. A classic example is the 1986 translation of Julius Wolff's book, which translators P. Maquet and R. Furlong titled *The Law of Bone Remodeling* [10]. However, Wolff named his treatise *Das Gesetz der Transformation der Knochen* [11]. (fig. below), using the term "transformation," which, in his view, is most accurate in expressing the essence of the issue at hand. If we use modern terminology, the adaptation in Wolff's law, as T.H. Smit and E.H. Burger [12] remark, is more of a law of modeling and not remodeling, since the growth, the surface drift and the bone's functional adaptation are all various forms of modeling. Remodeling, on the other hand, is the local resorption and the consequent formation of bone tissue in that area, a process that replaces old bone structures with new structures, which originate without the change of the bone's geometric parameters.

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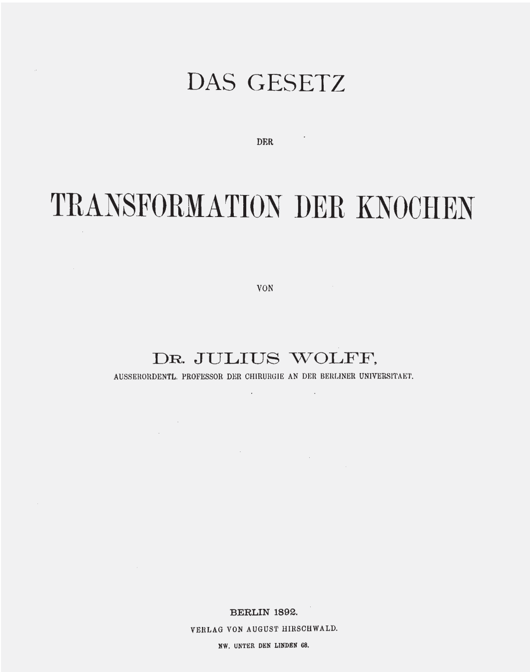
DAS GESETZ

DER

TRANSFORMATION DER KNOCHEN

VON

DR. JULIUS WOLFF,

AUSSERORDENTL. PROFESSOR DER CHIRURGIE AN DER BERLINER UNIVERSITAET.

BERLIN 1892.

VERLAG VON AUGUST HIRSCHWALD.

NW. UNTER DEN LINDEN 68.

Title page of Julius Wolff's work, Das Gesetz der transformation der Knochen (Berlin, 1892).

In other words, the more distant a particular scientific event is from us, the higher will be its level of "modernization" with the use of words whose definition greatly distorts the meaning of the depicted scientific phenomenon. In this regard, Wolff's law is not an exception. In the context of the issue under discussion, additional difficulties arise because not all specialists have access to the original source, since not many libraries possess Wolff's manuscripts. Moreover, his texts are written in 19th-century German, which presents additional problems for reading them in translation. Thus, Wolff's works are practically inaccessible for most Russian orthopedists, traumatologists, osteologists and other specialists.

The purpose of this article is to briefly describe the historical conditions in which Wolff discovered the law of bone transformation and to offer a translation from the German of the first fragments of his treatise *Das Gesetz der Transformation der Knochen* (Berlin, 1892).[1]

[1] This article is an English translation of a Russian article. The original Russian article contains the translation of Wolff's treatise from German into Russian (in the appendix), made by specialists in the history of medicine. Before that, there were no translations of this treatise into Russian.

Brief biography (according to R. A. Brand [13])

Julius Wolff (1836–1902) was born in March 1836, in Märkisch Friedland in Western Prussia (currently Mirosławiec, Poland). After graduating from the gymnasium he entered the Frederick William University (currently the Humboldt University of Berlin), where in 1860, under the supervision of Bernhard Langenbeck (the founder of the journal *Langenbeck's Archives of Surgery*), he defended his dissertation *De Artificiali Ossium Productione in Animalibus*. In 1869, Wolff married A. Weigert and had three children, one of whom died at the age of six. The Jewish Museum Frankfurt boasts 168 of Wolff's private letters, which attest to his faithfulness to his family and to his love of classical music and literature, and which demonstrate that he wrote poetry for his nieces and nephews. According to his wife's recollections, Wolff got up every morning at 5:00 a.m. and dedicated at least three hours to his studies. In 1864, Wolff participated in Prussia's military campaign against Denmark, in 1866 against Austria and in 1870–1871 against France, after which he was decorated with the Iron Cross. In 1868, he read lectures at the university, became a privatdozent and opened a private practice and then even his own institute, Privatinstitut orthopadische Erkrankungen (The Private Institute of Orthopedic Diseases). In 1884, Wolff was appointed Visiting Professor at the university. In this period orthopedics as a discipline was beginning to diverge from surgery, and in 1889, dean of the Charité Medical University Wilhelm Waldeyer-Hartz (1836–1921) petitioned the government to make Wolff a full professor at the university. Other professors at Charité[2] – such as pathologist R. Virchow, surgeon E. von Bergmann, therapist E. von Leyden and pediatrician E. Enoch, who were interested in the results of Wolff's studies – supported the petition. In 1890, Wolff's institute became a part of the Frederick William University as a private clinic directed by Wolff himself. In 1894, his institute was named the Clinic of Orthopedic Surgery. In 1899, for his extraordinary

[2] The clinical building of the university's clinic in Berlin, the largest hospital in Europe

contribution to the development of medicine, Wolff was appointed Privy Medical Councilor.[3] In 1902, just a few months before Wolff's death from a cerebrovascular disorder, the 30-bed orthopedic clinic was fully incorporated into the Charité Medical University.

On the historical factors of the second half of the 19th century and the appearance of the new scientific school – skeletal mechanobiology

Any scientific discovery is based on results obtained by previous scientists in the course of their studies. Among the most important factors that helped Wolff lay down his "law of transformation" were the development of German engineer Karl Culmann's (1821–1881) method of graphical statics, the use of this method in mechanics and the publication of the first essay on this topic. Using the example of a prismatic beam fixed at one end and weighted on the other (free) end, Culmann was the first to demonstrate the distribution of stress, which in scientific literature subsequently became known as principal stress trajectories [14, 15].

In 1867, Swiss anatomist G.H. von Meyer published drawings of the internal structure of the proximal end of the femur, which laid the foundation for his collaboration with Culmann. It was the first time that an engineer and an anatomist conducted a serious joint study of the influences of mechanical environment on trabecular architecture [16]. The collaboration evolved from a dialogue between Culmann and von Meyer: when von Meyer showed the internal architecture of the femur, Culmann exclaimed, "This is my crane!" [17] The results of their collaboration attracted the attention of W. Roux, who introduced the term "functional adaptation." However, although Roux was the first to mention it, the concept of functional adaptation was later attributed to surgery professor Julius Wolff [18].

On Wolff's role in the establishment and development of mechanobiology

In the context of the issue under discussion, it is important to understand that it was Culmann and von Meyer who were the first to show the interrelation between the variations of internal mechanical stress and the alignment of trabeculae. Wolff supported this concept two years later and his main accomplishment, in the opinion of C.R. Jacobs [16], was in popularizing this idea and ensuring its recognition by a vast medical community. Wolff dedicated a large part of his publications to the concept of trabecular alignment, which he called the Trajectorial Theory. At the same time, he delivered enthusiastic lectures in which he illustrated with many examples the reorientation of trabecular alignment following a change in internal stress patterns, which can occur when a fracture heals with the fragments incorrectly aligned. Wolff's theory was indisputable at the time. He is often credited with having discovered cancellous bone adaptation, and his contribution to the popularization of the scientific discipline that emerged at the crossroads of biology and mechanics is still highly esteemed today. The school that he popularized, mechanobiology, has not only scientific but also clinical significance.

In his Trajectorial Theory, Wolff affirmed that trabeculae always intersect perpendicularly to each other. He made the conclusion using an established fact in mechanics, according to which internal stress directions always intersect perpendicularly for any given loading case. Since trabeculae align themselves with the stress directions, the architecture of the cancellous bone, therefore, forms a network of perpendicular intersections. With this logic Wolff criticized von Meyer's anatomical drawings, which were based on studies of postmortem samples and thus could not show the architecture of perpendicular intersections.

In essence, Wolff limited his approach by creating an ideal situation in which the mechanical environment is characterized by a single or predominant load. He thought that the adaptation of cancellous bone was outside his qualitative observations and could be understood in terms of a "law according to which alterations in the internal architecture followed mathematical rules" [16]. And although according to the modern point of view the daily stress of a skeleton creates a mechanical environment that cannot always be effectively supported by the perpendicular structure of trabecular intersections, Wolff's

[3] Honorary title of a doctor in public service.

merit lies in having initiated scientific interest in the adaptation aspects of cancellous bone mechanobiology.

Publications that review Wolff's law on the processes of bone-adaptive reconstruction rarely note that the law's formulation concerning bone shape and function is based on the static mathematical relation between the trabecular architecture and the stress trajectories. Wolff also avoided studying the mechanisms of adaptive behavior in individual cases, believing that the bone's "shape" would be inherited. The main principles of Wolff's law and his incorrect ideas on skeletal biology appeared not only because of the limited methods accessible to him at the end of the 19th century, but also because of his refusal to accept facts that were recognized at the time. For example, according to Wolff, the "function" was the bone structure's static stress. This view significantly differed from the ideas that W. Roux expressed in his treatise on dynamic interaction. He also believed that the bone increased only through interstitial growth. Wolff rejected the idea of resorption, although this mechanism had already been described by A. Monro (1776) and J. Howship (1816). Nevertheless, despite the incorrect interpretation, Wolff's law became a conventional theory. As M.R. Forwood and C.H. Turner [19] emphasize, "it seems that the fact that Wolff was incorrect concerning all the biological aspects of "his" law does not worry anyone very much. References to W. Roux can be found only in the historical book collections of good libraries" [19]. Additional information regarding the historical factors of the second half of the 19th century that contributed to the appearance of skeletal mechanobiology as a separate scientific-clinical discipline can be found in the work of S.V. Arkhipov-Baltiisky [20].

It is important to note that while at the end of the 19th century, Wolff believed that the bone's "shape" is inherited, more than one hundred years later, in the 21st century, Wolff's law has been harshly criticized by C.O. Lovejoy and his coauthors [21], strictly from genetic positions. These authors dedicate an entire section of their work to this problem. Since the law is of utmost importance in understanding the issues under discussion, we will briefly explain its principal elements.

Wolff's law: a new interpretation of the role of deformation for bone morphogenesis

As C.O. Lovejoy and coauthors emphasize [21], the idea that bone structure forms according to Wolff's law dominated 20th-century thinking on the subject. The law states that through the activation of unknown mechanisms the bone is able to transform loads into precise changes of internal architecture with analogous secondary changes in the outer structure in accordance with mathematical laws. Such ideas led to the popularization of the contrary theory that the bone's shape can be used for restructuring actions that have "produced" the shape on condition that the "mathematical laws" are known, while the adaptation and actions can be obtained from geometrical studies of bone structure. The law also ignores the anabolic aspects of gene expression, which have been inadequately studied. In this regard, the authors affirm that more is known about skeletal genetics than about "mathematical laws," according to which bones theoretically model themselves. The authors emphasize that although there is a significant amount of information on bone behavior under mechanical loads, what remains unclear are the laws according to which the required result of bone formation is achieved through the use of an unknown set of mathematically similar transduction functions, despite former attempts to determine these laws [21].

This genetic approach to examining adaptive processes of skeletal architecture formation should not be seen as overly tendentious. However, it is also necessary to take into consideration the fact that bone shape always changes when the character of its functional activity changes. This cohesion of mechanobiological factors occurs in early development when the embryo's cellular structure begins to experience deformation and pressure, and it continues to have an effect during the organism's growth, development and ageing. Researchers in the fields of biology and medicine for various pathological and physiological conditions are greatly interested in the influence that biophysical stimuli have on the skeleton's growth and adaptation.

Essentially, Wolff's concept and law form only one of the existing models that reflect the characteristics of skeletal mechanobiology. As with any model, it is a simplified copy of natural events, with all the merits and shortcomings inherent in the modeling of natural processes. In this regard, it is important to note that this conceptual model for predicting the development of reparative and regenerative processes in orthopedic-traumatological practice is still being used today. A more detailed examination of the merits and shortcomings of Wolff's model would require special study.

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