Chapter 1
The Perfect Human Machine

Nature provided its genetically engineered living products with considerable built-in self-assembling and, moreover, auto-repair capabilities. The example *par excellence* is the human body and for the reasons just mentioned, we quote it as a *perfect machine*. The excessive efforts by top athletes definitely provoke microfractures in muscles, bone and tendons but these fractures are continuously repaired on condition they remain below the critical level of damage. The same holds for hard tissue, which is constantly remodeled under stress. However, it is not failure free. Main reasons for failure are: accidents provoked by extra-corporeal interventions, genetic accidents, physiological accidents and natural (built-in!) auto-destruction at cellular level, i.e., natural cell death or *apoptosis*. Biomaterials figure as main partners in the production of devices for relieving the inconvenience of the last two reasons of failure and to assist the repair of the first reason of failure. Figure 1.1 is a nice archaeological example of the first: a man's tibia, broken in a nondocumented accident around the turn of the first millennium. The healing is not beautiful but anyway, the fracture healed with at best primitive if any surgical help.

1.1 Biomaterials: Philosophical Background

Thinking and talking about *biomaterials* is to some extent still done in car mechanic terms: what component of the engine failed, how can it be repaired or substituted by the appropriate spare part? This is not merely a caricature of biomedical speech but is rooted in western European philosophy. The herald of speaking about the human body in machine terms is credited to the sixteenth century anatomist Andreas Vesalius; his brilliant book *De humani corporis fabrica* was published in Basel, Switzerland, in 1543 [2]. The human anatomy is described herein with amazing accuracy as an assembly of functional spare parts. Outside its value as a milestone in anatomy, the book is a jewel of printers' skill and the plates are pure art! The mechanistic concept gained gradually official status in western European philosophy through the seventeenth century philosophers, e.g., Descartes [3]. They denied

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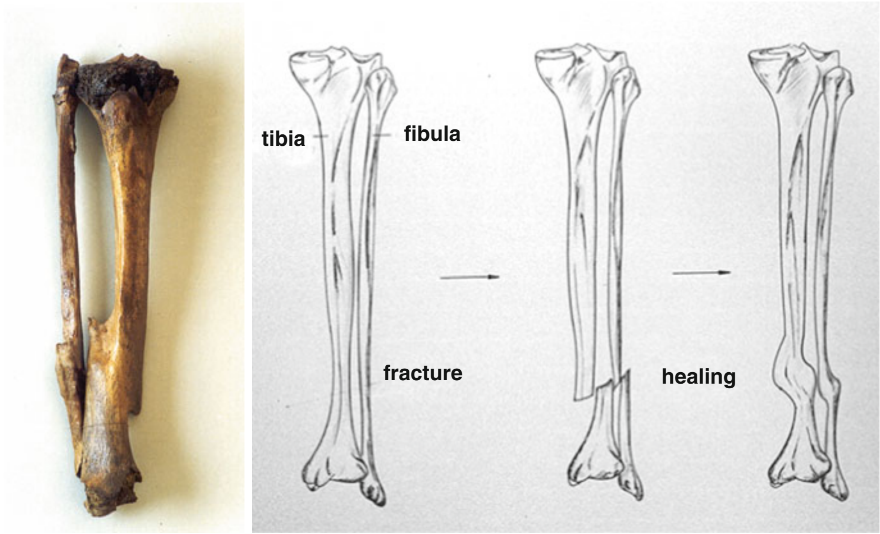


Fig. 1.1 Healed tibia and fibula of a man living around the turn of the first millennium. Courtesy of the *Wetenschappelijk en Cultureel Centrum van de Duinenabdij en de Westhoek, Koksijde, Province of West Flanders, Belgium*

the Aristotelian way of thinking that nature consists of what can be called *conscious dust* and hypothesized that nature, including living matter, was built up from particles of *inert matter*. A logic consequence was that these philosophers asked the question: *are humans machines?* Therefore we "adapted" the famous text in the book *Epidemics* of the Hippocratic Corpus [4, p.165]:

> Declare the past, diagnose the present, foretell the future; practise these acts. As to diseases, make a habit of two things: to help, or at least to do no harm. The art has *four* factors, the disease, the patient, the physician and *the engineer.*

Including the engineer, or be it a materials scientist, chemist or physicist, into the medical business justifies that the development of implants and the materials to make them is all overarched by the term *biomedical engineering*.

The performance of materials of interest to this book is intimately linked to the implant locus and consequently, the generic classes of materials will be discussed, where possible or relevant, starting from a case study. Let us first try to define the term *biomaterials*.

Till half a century ago, a material happened to be a biomaterial by lucky accident or educated guess. A metal, ceramic or polymer could accidentally exhibit an *ensemble* of properties, which made it suitable for covering a broken tooth, because it accidentally happened to have sufficient wear resistance, was not corroded when drinking Coca Cola, was not deformed when biting in a half-ripe apple, was not poisonous, was not giving bad taste in the mouth... Such a material was so-called biocompatible, was quoted as a biomaterial but, let it be clear, for that particular application. The same alloy, e.g., a gold alloy, is occasionally suited for manufacturing a vascular stent but will definitely not be appropriate for a hip or knee prosthesis. Herewith we wanted to state that *biocompatibility* is somewhat a confusing term: the required performance of a material used is too different from one site in the body to another that a general definition will be either too vague or too restrictive! The same concern was expressed by Jonathan Black, where he preferred the term *biological performance* instead of biocompatibility [5]. A definition we propose is:

> A biomaterial is any material, single member of a generic class or a combination of two or more members out of the same or different classes, which can be used in a living body for a particular implant or group of implants, which does not incite negative response by the body, which is stable or exhibits only controlled and well-assessed breakdown.

It is a definition with all pros and cons of any other definition and many others can be found on the web. Admittedly, it is a definition that biocompatibility restricts to the ability of a material to perform with an appropriate host response in a specific application and meets, to some extent, David Williams' remark that *the adjectival counterpart 'biocompatible' should not be used because there is no such thing as a biocompatible material* [6]. Of course, along the same lines, one could say that there is no such thing as a biomaterial!

An implant, however good it may be, remains a foreign body and triggers a defense reaction, a clear proof of the interaction between body and implant. This interaction may be positive, wanted, if possible stimulating tissue growth or remodeling, or negative with respect to body and/or implant and to be avoided. In between exists a grey zone of indifferent behavior, if indifference exists at all in a living body. Biomedical research tries to grasp the puzzling interaction mechanism between body and implant with the ultimate goal of tailoring materials, optimized with respect to as many requirements as possible for a given *optimized shape*. Different from Vesalius' time is that physicians today are aware that malfunction of an organ has almost always a complex set of causes; beyond doubt, however, remains evident that the animal body is subject for part of its function to purely mechanical constraints and the biological materials are designed to meet these particular constraints. Implants and the materials to make them should, as far as possible, meet these requirements too. The right tailoring of materials and implants remains the goal for at least another two decades. That is how we see it today but what tomorrow will bring us might be another story: computational biologists may be the future rulers in the field. These newcomers apply computer simulations, increasingly paired with experiments, to understand and predict the quantitative behavior of complex biological systems and in the next stage drive new experiments [7]. Do not forget, however, the warning formulated in the Preface on complex systems and emerging properties.

1.2 Staying Alive Despite the Second Law

A living body is not a closed but an open system and through this the body deceives physics. It puts a brake on an uncontrolled increase in entropy ΔS, i.e., the increase of heat content ΔQ per degree Kelvin, heat being the least noble form of energy. A body is a complex biological system that by a self-regulating process maintains a dynamic stability for all vital parameters (temperature, ionic concentration, metabolic rate, energy conversion…). The process is called *homeostasis* or, as some authors prefer, *homeodynamics* because of the dynamic character of the process. *Self-regulating* may be substituted by *negative feedback* which is the basic principle of a branch of science named *cybernetics*. Feedback is a mechanism that reacts to disturbance of conditions through modifications of equal size and opposite direction. The disturbance may concern the global body, for example change of external temperature or humidity of the environment, or local parts, for example a change in ionic concentration at an implant interface. Feedback tries to maintain the internal balance. A sustained disturbance may go beyond the capability of the feedback mechanism to reestablish equilibrium and at that point, the mechanism itself may become destructive for the system it is intended to protect. The overencapsulation by fibrous tissue of the stem of a hip prosthesis, the inhibition of apposition of new bone and the subsequent failure of stability may be understood in these physical terms.

The foregoing paragraph seems not to learn us anything how implants should be improved or manufactured. The intention was to introduce homeostasis as the iron consequence of the physics of complex open systems. Although at first sight it is far away from the prosaic reality of biomaterial business, it is not. In testing the biological performance of a material or a device *in vitro*, the compelling dynamic character of the body site, in which it is intended to function, is often ignored in the concept of experiments.

1.3 Scaling of Plants and Animals

Since the time of Vesalius, the machine concept of the human (or animal) body has continued to develop till today. Seventeenth century masterpieces and milestones in this respect are the studies of blood circulation by William Harvey (1578–1657) *De Motu Cordis et sanguinis in animalibus, Anatomica Exercitatio* [8] and the motion of animals by Giovanni Alfonso Borelli (1608–1679) in *De Motu animalium* [9]. These are descriptions in qualitative mechanical terms of those magnificent running, swimming or flying *machines*. The interplay between geometry, physics and mechanics, be it of rigid bodies, fluids or gases, and biology is obvious, and is translated in a number of mathematical laws.

Leonardo da Vinci was already fully aware of this interplay. He was dreaming that, one day, it would be possible for man to sustain himself in the air by modifying the structure of the body through the addition of wings. For this purpose, he studied the flight of birds and introduced scaling principles:

> With wings expanded the pelican measures five braccia, and it weighs twenty-five pounds, its measurement thus expanded therefore it to the square root of the measurement of the weight. The man is four hundred pounds and the square root of this figure is twenty: twenty braccia therefore is the necessary expanse of the said wings. [10, pp. 25–26]

Leonardo's scaling law was not to blame for its oversimplification because five centuries later fanatics of maths and biology are still busy refining scaling laws: man cannot fly for a complex set of mechanical and physiological reasons. One of those fanatics was D'Arcy Wentworth Thompson who published in 1916 *On Growth and Form*. Although willingly ignored by many of contemporary colleagues, it is a real masterpiece, still readable as witnessed by the recent reprints of the unaltered republication by Cambridge University Press of 1942 [11]. Kleiber's law (1932) is following the same philosophy; it is an allometric scaling law of which the mechanistic part became theoretically well underpinned during recent years. Max Kleiber (1893–1973), a Swiss agricultural chemist, joined the Animal Husbandry Department at the University of California, Davis, in 1929 to study the energy metabolism of animals [12], [13, Chap. 10]. The conclusion that all biological structures were affected by their size is a result of his studies. The allometric scaling of a biological variable Y with the body mass M is of the form

$$Y = Y_0 M^b, \tag{1.1}$$

where b is a scaling exponent; Y_0 is a constant, characteristic of the kind of organism. The basal metabolic rate scales as $M^{\frac{3}{4}}$. If simple geometric constraints were involved, one would expect multiples of one third for the exponent b. However, many biological phenomena scale as multiples of one fourth with body mass. West and colleagues proposed a mechanism underlying these laws: *living things are sustained by the transport of materials through linear networks that branch to supply all parts of the organism* [14]. The $M^{\frac{3}{4}}$ behavior of branching by space filling fractallike networks can be derived analytically [15, pp. 63–66], [16]. This law is experimentally confirmed over 18 orders of magnitude (unicellular organisms to whales) [12]! Mammalian blood vessels, the bronchial network or vascular systems are examples of such networks. In this paragraph we discussed so far one example of biological scaling. Next, we want to explore what happens to the ratio of mechanical variables like limb length and diameter or, say, the elastic properties, when the size of bodies increases? Let us first see what we can learn from trees!

During growth, the root system of a tree is optimizing its shape in order to account for the load distribution at the top of the tree. Mechanical analysis shows that during growth the geometry of the root system tends to minimize stress concentration. For an unbalanced load distribution, the case for a tree on the edge of the wood, the root system will have an 'optimal' shape different for the tensile and compression side as shown in Fig. 1.2. The same holds for the shape of the implant zone of the branches, bifurcating branches, etc. The subject is treated *in extenso* by,

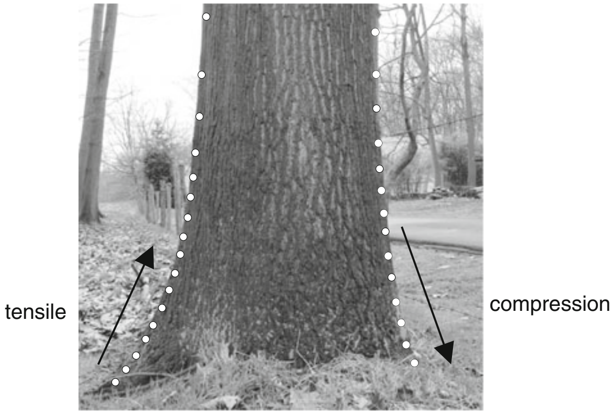


Fig. 1.2 Trunk of an oak. The tree is situated at the edge of the wood. More branches are pointing away from the wood with unbalanced loading as consequence. The root system accommodates its shape to minimize the stress distribution on both sides of the trunk

e.g., Claus Mattheck [17]. It is an example of the ingenious biological minimization of mechanical stress. In the design of implants, sharp edges will be avoided not exclusively but often for reason of stress distribution.

The slender construction of a tree has a length to diameter ratio $\frac{l}{d} > 25$. A column height l and diameter d collapses when its total weight exceeds the maximum compressive stress σ_{max}. A small lateral displacement applied on too slender a column will make it collapsing at what is called the critical length l_{crit} for buckling. For a cylinder, the critical length is related to diameter by:

$$l_{crit} = k \left[\frac{E}{\varrho} \right]^{\frac{1}{3}} d^{\frac{2}{3}} \tag{1.2}$$

with ϱ the mass per unit volume (specific mass) and E the elastic modulus.[1] The constant k is 0.851 for a cylinder but changes with the shape of the column, tapered or any other form, while the exponent $\frac{3}{4}$ remains the same. For bending, an exactly identical equation is valid but the constant is different. The law is verified by a collection of quantitative observations on trees, representing almost every American species. Tree height plotted versus trunk base diameter on a double logarithmic scale fit to a line with slope $\frac{2}{3}$ (Fig. 1.3). Trees are said to maintain *elastic similarity* during growth.

A total of 576 records of tree height vs. trunk diameter are plotted in Fig. 1.3: the dotted line is the best fit through the data points with slope $\frac{2}{3}$. It is parallel to the solid line, calculated according to (1.2) and taking $E = 1.05\,\text{MPa}$ and $\rho = 6180\,\text{Nm}^{-2}$;

[1] Mechanical terms and definitions are collected Sect. 1.4.

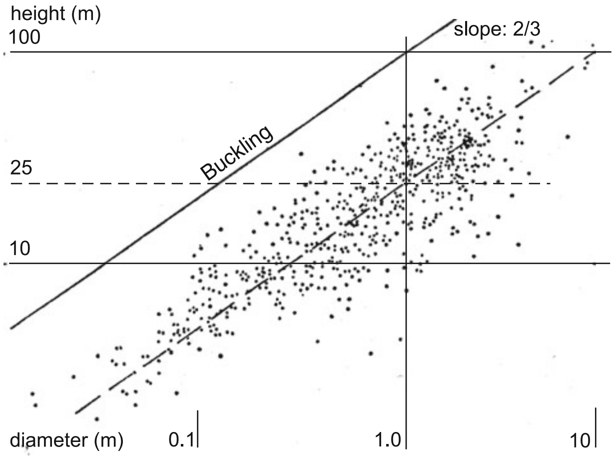


Fig. 1.3 Double logarithmic plot of overall height versus trunk base diameter of trees. The grey zone encloses 576 records representing almost every American species. The best fit is the dotted line with slope 2/3 and parallel to it, the solid line, calculated by (1.2). Adapted from [18]

E/ρ is fairly constant for green woods. This good fit leads to the conclusion that the proportions of trees are limited by elastic criteria (no data points above the calculated solid line). A second conclusion honors nature's prudence: the height of most records is about one fourth of the critical height for buckling, a fair safety factor. A common factor in engineering is 3 but apparently, plants play at the safe side.[2]

An issue of the discussion above is the importance of the elastic modulus, in general and during plant growth in particular. What about animals? How do they adjust their shape to scale? If scaling would be determined only by the strength criterion, animals *would grow no larger than a size which makes the applied stress equal to the yield stress of their materials*. Animals follow the same scaling exponent as trees: limb length, measured parallel to the direction of compression or tension, scales with the $\frac{2}{3}$ power of diameter. If this is true for quasicylindrical elements and simple loading geometry, it remains true independent of the type or combination of gravitational 'self-loading', static or dynamic. Also total body mass, chest circumference or body surface are subject to exponential scaling.

An important scaling law is the relation between metabolic heat production and body weight. The power output of a muscle fiber depends on the flow of energy, which in turn is proportional to its cross-sectional area. The fiber is a fraction of the body mass M and its diameter d is, from geometrical arguments, proportional to $M^{3/8}$. The cross section of the fiber is proportional to d^2 and hence, to $[M^{3/8}]^2$ or simply $M^{3/4}$. That is schematically how the allometric scaling law of Kleiber

[2] In a recent paper Kolokotrones et al. presented an interesting nonlinear model on the logarithmic scale for metabolic scaling. See [Nature 464, 753–756 (2010)].

was deduced with its magic exponent 3/4 in (1.1). The former discussion is based on [18–23].

For the discussion on scaling laws we went far back in history, against the current trend to confine citations to papers of say the last five or ten years, blinded as we are by the achievements of computer-assisted modeling, finite element analysis and the like. The papers we referred to, however, remain readable literature. Speaking about the branching pattern of trees in 1976, McMahon and Kronauer state that it is approximately stationary within any species and *That this means, that the structure is self-similar with respect to the parameters we recorded ... the elastically similar model provided the best fit* [20, p. 460]. Their statement preceded by many years the hype that the concept of self-similarity as part of the definition of fractals provoked by Mandelbrot's publication in 1983 [24].

Searching universal laws is an integral part of any science. Kleiber's $\frac{3}{4}$ power law is one of these universality attempts in biology. It seems to be mathematically well underpinned (although the discussion is definitely not closed). The scaling laws bring us automatically to the concept of fractals, which by West et al. are beautifully quoted as the *fourth dimension of life*. These authors state that: *Natural selection has tended to maximize both metabolic capacity, by maximizing the scaling of exchange surface areas, and internal efficiency, by minimizing the scaling of transport distances and times. These design principles are independent of detailed dynamics and explicit models and should apply to virtually all organisms* [14].

One example of these principles are the arteries and veins (transport of nutrients and waste!) in the mammalian body. Although arteries, veins and blood represent only about 5% of the weight, blood vessels are found within a distance of a few cells throughout almost the whole body, a rare exception being the vascularity of the cornea required for optical clarity [25]. Nature devised here an utmost efficient bifurcating distribution system, already described by Leonardo da Vinci, although he considered veins and arteries as transporting heat [10, Chap. VIII]. It would last another hundred years before the real function was revealed by Harvey [8].

In Euclidean objects, mass (M) and length (L) scale with integer exponents (3 in this case). Many biological 'objects' show non-Euclidean order and scale with noninteger exponents. The network of blood vessels is an example, the structure of lungs is another, both are scale invariant and self-similar. Detailed definitions on fractality and self-similarity are beyond the scope of this textbook but for this purpose Mandelbrot is the original source [24]. This subject is referred to here because it is intrinsically linked to the discussion on scaling. Moreover, the bifurcating and pervasive vascular network explains why, a couple of decades ago, the intense investigation on ingrowth in porous surfaces for dental and orthopedic implants failed and why currently massive tissue substitutes fail.

Reference to scaling and/or fractality is not common in biomaterials literature. Why then should this relatively long discussion on biological scaling laws be relevant in the context of this book? Does it contribute anything to the discipline? A number of reasons compel us to answer yes.

Universal laws. It is the statuesque beauty of science that it is searching for an ever smaller number of principles from which particular cases can be deduced. Scaling laws belong to that category. Application of this principle finds not only its place in 'big science'! Science starts at the bottom with decently interpreted experiments. Help in seeing the light through the burden of data can be triggered by reduction and/or normalization of data. These simple tools can be basically instructive but inspection of the current literature indicates that they are often neglected, forgotten, or worse, not known anymore. Below we discuss an example. The same holds for statistical data treatment and data reduction [26].

Understanding processes. In Fig. 1.4 (top) are displayed setting curves of brushite cement, monitored by FT-IR absorbance at a given wavenumber; the parameter is retardant concentration (details are not important for the present discussion). 'Macroscopic' difference in rate is easily registered by simple inspection of the graphs but subtle differences between those three curves is not. If the reaction mechanism is independent of retardant concentration, the curves should overlap

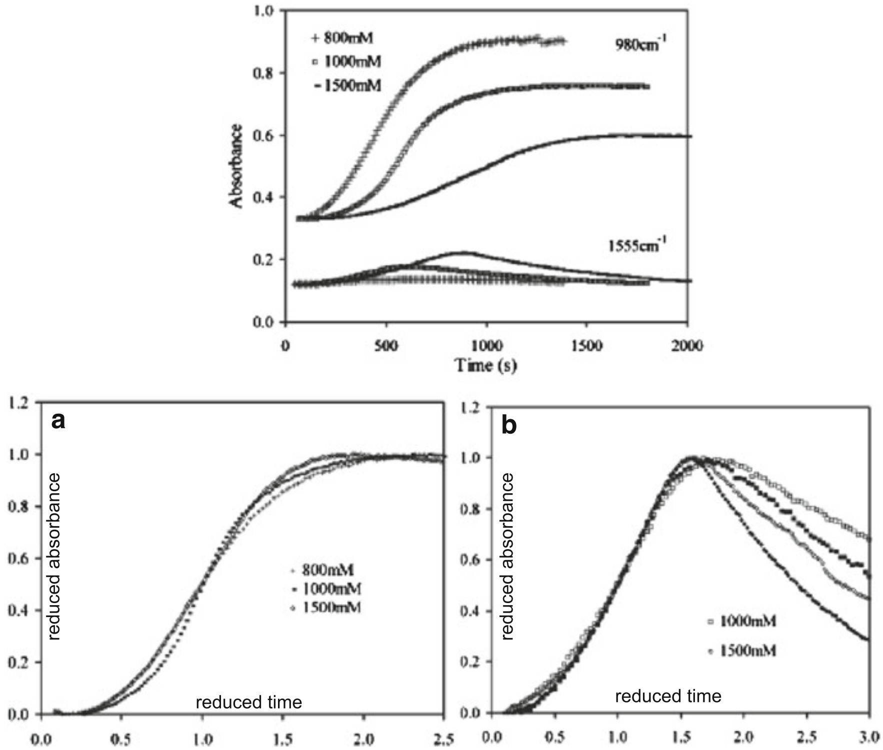


Fig. 1.4 Setting kinetics of brushite cement (FTIR-monitoring). (**a**) IR-absorbance vs. time (s) for three concentrations of retardant; (**b**) normalized absorbance vs. reduced time $t/t_{0.5}$, t divided by the time to complete 50% of the reaction. Adapted from [27]. Reproduced by permission of the Royal Society of Chemistry

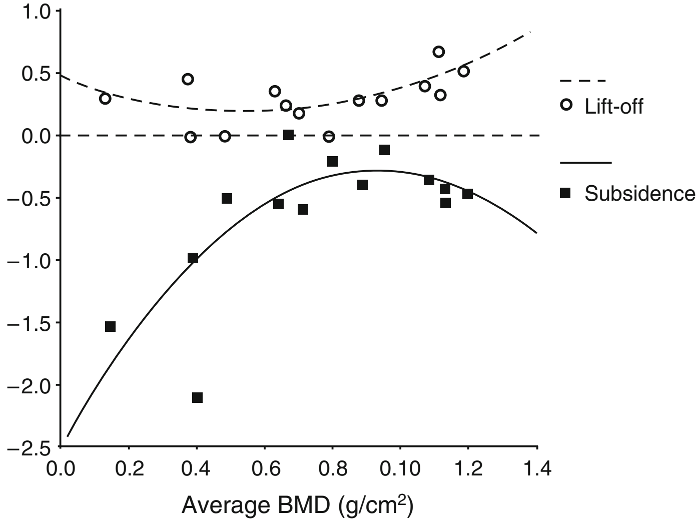


Fig. 1.5 Subsidence and lift-off (mm) of an uncemented total knee tibial plateau versus average bone mineral density. Courtesy Luc Labey [28]

on normalizing. They qualitatively do as seen in (a): the reaction mechanism is probably the same irrespective of the retardant concentration; however, the small differences between the curves point to differing formation rates of the sequence of intermediate compounds and/or to conformation differences, for example diffusion hindrance, in the heterogeneous matrix; in (b), however, clear rate differences exist above $t/t_{1/2}$, not easily observed in the original data. This one example from literature is rather the exception than the rule. On the contrary, curves fitting by more or less sophisticated computer programs is good fashion, can be of help in technological applications, but does not help science to progress: a physical model should underlie the analyzed data. The reference is given to emphasize that 'old-fashioned' techniques are still valid today. Detailed understanding of a process allows more intelligent experiment planning, reduces the number of experiments and is occasionally applicable to similar processes: it is the way up from a particular system to a more universal level. Science?

Understanding functions. In a study of migration of the tibial component in a total knee arthroplasty, Li and colleagues found a relationship between bone mineral density (BMD) and subsidence [28, 29]. An obvious clinical conclusion is that there seems to be an optimal range of BMD, and no doubt, it is a clinically relevant observation. The authors fit a nice curve through the experimental data but do not supply, not even suggest, a biomechanical or physiological explanation. We have no data available for a thorough analysis but, based on insight in the structure of bone we would not be surprised to see the given relationship analyzed in terms of a multifractal response of the solicited bone structure (see for example [15, Chap. 9]).

Self-similarity. In one of the following chapters, we will examine materials for scaffolds. But first this: we selected at random two papers on scaffolds by Schantz et al. and Manjubala et al. [30, 31]: different preparation techniques, different materials, etc. (details not relevant for the present purpose), scaffolds with 3D architecture. The produced product is geometrically regular and thus dimensionally self-similar. The self-similarity we were referring to a few paragraphs back will not fit this geometric model. In a recent paper, drug release is reported from an *ordered* silica material. Order might not be an obstacle here because at the nanoscale the process is going on but who will pretend that a distribution of pores would not result in a more regular drug delivery [32]? Biologic order is non-Euclidean!

By foregoing thoughts biomaterials research was projected on a broad biologic and scientific background. The purpose was to demonstrate that in installing 'biospare parts' here and there in the body, a sound holistic view on the body is unmistakably a safe guide in research. Not that the holistic view helped the individual patient but it could have helped the biomaterials community, when it was investing in bone ingrowth in porous coatings during the 1970s to pay simultaneous attention to vascularization. Only now is appearing an awareness about it in the booming area of scaffolds as was already mentioned, an item on which we will come back later. We could not refrain from ventilating some criticism on current shortcomings in scientific reporting, fully aware of our own sins in the past. Further useful reading on scaling is the book *Fluctuations and scaling in biology* [33].

Statistical analysis. Before walking to the next section a parenthesis on statistics. Statistical data treatment of, say, mechanical properties may look less stringent. In 'Fire of Life' Kleiber paid special attention to statistics: he even summarized the 'The Twelve Commandments of Biostatistics' which still sound unbelievably alive [13, p. 385]. Computer facilities make statistical analysis easy to day, too easy and often applied undiscriminatingly. Many good textbooks exist but as a first aid 'Statistical Rules of Thumb' by Gerald van Belle [26] is warmly recommended. Only a sound application of statistics can be of any really valuable help! Outside the basics, items like sample size (a pertinent question for all investigators in the field), covariation and in particular a critical chapter (pp. 153–173) on 'Words, Tables and Graphs' worth the following illustrative excerpt of van Belle's rules of thumb:

1. Use text and not a table for displaying few numbers (2–5).
2. Limit the number of significant digits in a table and convey crucial information in the heading!
3. When possible always graph the data. The graphs given by van Belle in Fig. 7.1 were taken from a paper by Anscombe [34]. They show how instructive a graph may be for interpreting statistics!
4. Never use a pie chart and always think of an alternative to bar graphs, or worse, stacked bar graphs (they are waste of ink!) or even worse 3D bar graphs (misdirected artistry!).

These are a few points about the use (and abuse) of statistics in a refreshing perspective.

1.4 Definitions

In this chapter, we wanted to stress through biological examples and scaling laws the interplay between pure mechanics and biology. The goal is that the designer should learn from nature. In the past, it was not simple to quantify nature, but today, even more detailed analyses and computer-aided simulations allow to penetrate natural processes with increasing accuracy. These simulations are all part of that learning process.

In this section, we define the current mechanical properties introduced thus far in the text. The meaning of these variables are easily illustrated graphically by the stress–strain curve given in Fig. 1.6. Inserted in the graph are the shapes of a test specimen at three stages during its deformation in a tensile machine. In a first approximation, the stress–strain curve is characterized by the elastic deformation zone, the plastic deformation zone (beginning of necking) and fracture. More complex curves will occasionally be given when materials such as superelastic alloys displaying complex deformation behavior are discussed.

Given are: *the name of the property (occasionally an alternative name): the current symbol, the dimension between [. . .] (with L for length, M for mass, T for time, [-] for dimensionless), basic units or their multiples (m for meter, g for mass,*

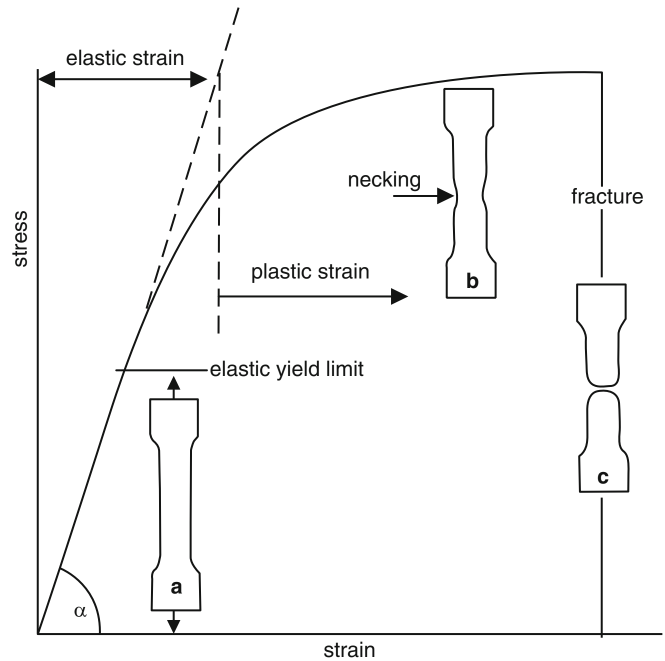


Fig. 1.6 Increase of strain (reduced length) of the specimen as a function of applied stress (load per unit area of cross section). All variables are defined in the text

s for second; the first figure refers to the SI unit); definition. The dimensions are useful to test the consistency of the units in a result of calculation through an equation or to define the units after deduction of an equation. Test specimens for the determination of mechanical properties are normally machined to standardized shapes and by standardized procedures. They can be found in national and international standards for testing materials listed, e.g., by Helsen and Breme [35, pp. 67–71]. The main units used and conversion factors in the text are summarized in Tables A3 and A4 (Appendix A).

Creep: ϵ, [-], %. Creep is a slow continuous deformation or strain under constant stress. It is function of stress, temperature and time. It only represents a problem for metals and ceramics near their melting or softening temperature. For polymers, however, is it sizable at low temperature (<200°C) and as such a major design parameter. Glass transition temperature is a criterion for creep resistance. A special kind of creep to mention is viscous flow and, it is, like diffusion, an exponential function of temperature and a linear function of stress:

$$\frac{d\epsilon}{dt} = C\sigma \mathrm{e}^{-\frac{Q}{RT}} \tag{1.3}$$

with t time, C a constant for a given polymer, Q the activation energy for viscous flow, R the universal gas constant and T the temperature in °K. C and Q are supplied by producers.

Density: ϱ, [$\mathrm{ML^{-3}}$], $\mathrm{kg\,m^{-3}}$ or with the same numerical value $\mathrm{g\,dm^{-3}}$; $\mathrm{kg\,dm^{-3}}$, $\mathrm{g\,cm^{-3}}$, g mL. It is a property that depends on the way atoms or molecules are spatially organized. It is measured as mass per unit volume; sometimes expressed as multiples of the density of a standard material (usually water at 4°C).

Ductility: A, [-], %. Ductility or elongation at fracture means strain at fracture, i.e., the strain at the high end of the stress–strain curve in Fig. 1.6. The reduction in area of the specimen at that point is a measure of ductility. It is the ability of a material to undergo large plastic deformation before it is breaking. In some instances, in addition to tensile tests, the reduction in area in the necking zone is given.

Elasticity modulus (Young's modulus): E, [$\mathrm{ML^{-1}T^{-2}}$], Pa, kPa (kilo-), MPa (Mega-), GPa (Giga-). The linear part of the curve below the elastic yield point is described by the famous law of the English seventeenth century scientist Robert Hooke (1635–1703): *ut tensio, sic vis* ('as the extension, so the force', published in 1676 in anagram form *ceiiinossttuuv*). The modulus of elasticity is determined by measuring the slope of the stress–strain curve, where strain is effectively proportional to stress. Measurement of sound velocity or vibration frequency are other methods to determine E.

Young's modulus is the macroscopic translation of the magnitude of interatomic forces and the packing of atoms (number of atoms per unit volume) and as such, it represents a fundamental physical property of matter. Atoms are held together either by strong primary bonds, ionic (Na^+Cl^-), covalent (as in diamond or in chains of carbon in polymers: –C–C–) or metallic (Fe–Fe), or by secondary bonds, Van der Waals forces (gravity attraction) or hydrogen bridging (between proton donor and a proton acceptor in polymers for example). The values of E-moduli may be as low as 0.1 GPa for low-density polyethylene or as high as 1,000 GPa for diamond, which has the highest modulus of any material.

Fatigue strength: σ_f, [$ML^{-1}T^2$], Pa, kPa, MPa. Materials may fail at stresses below the UTS or YS (see below) by exposure to repeated stress cycles. ASTM defines fatigue strength as the limiting value of stress at which failure occurs as N_f, the number of stress cycles, becomes very large. It is the stress level for steel and the like below which fatigue failure never occurs (<endurance limit). More ductile materials such as aluminum do not have such a distinct limit and these are tested on fatigue by subjecting to given stress amplitudes and up to a fixed number of cycles, usually $N = 10^7$. Fatigue strength is an extremely important engineering and design property.

Fracture toughness: K_{Ic},[$ML^{-3/2}T^{-2}$], $N\,m^{-3/2}$ or k- or $MPa\,m^{1/2}$. Fracture toughness is a property which describes the ability of a material containing a crack to resist fracture. It is an important property for all design applications. The subscript "Ic" denotes *mode I* crack opening under a normal tensile stress perpendicular to the crack. Numerically it is always smaller than the yield strength. For a condensed treatment of this property, we may refer for further reading to Ashby and Jones [36, pp. 131–139].

Friction coefficient: μ, [-]. The force that will just cause two materials to slide over each other, is called the static force F_s, and is proportional to the force acting normal to the contact surface; once the sliding started, the frictional force decreases slightly but remains proportional to the normal force acting on the sliding surfaces:

$$F_s = \mu_s P \;\; and \;\; F_k = \mu_k P, \tag{1.4}$$

where μ is the proportionality or friction coefficient, respectively, for the static and the kinetic case. Numerical values are difficult to give because they depend on the material, surface finishing and lubrication.

Rigidity modulus: see Shear Modulus.

Shear modulus: G, [$ML^{-1}T^{-2}$], MPa, GPa. While Young's modulus describes the response of a material to linear strain, the response to shear strain is described by the shear modulus.

Strain: ϵ for nominal strain or γ for shear strain, [-], fraction or %. Materials respond to stress by straining. The degree of strain depends on the elasticity modulus: a stiff material strains less than a compliant material under a given stress. The change of length l and radius r of a cylinder of a material is measured as function of the applied stress. Strain is calculated by taking the ratio of change in length to original length l_0 and of change in radius to original radius r_0, called, respectively, tensile strain or lateral strain:

$$\epsilon_{\text{tensile}} = \frac{l - l_0}{l_0} \;\; and \;\; \epsilon_{\text{lateral}} = \frac{r - r_0}{r_0}. \tag{1.5}$$

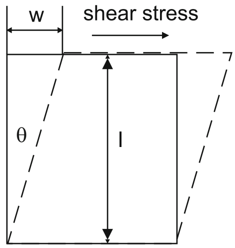


Fig. 1.7 Induction of shear strain by shear stress

The negative ratio of lateral strain to tensile strain at a given stress is called the *Poisson ratio* ν. Its value is ~0.3 for most metals (steel, Ti, Cu, ...) in the elastic range, for glass ~0.2 and for rubber, an upper extreme, ~0.5.

Shear strain: When the sample is not subjected to tensile or compressive stresses but to shear stress, the deformation is defined as shear strain. If a given shape, say, a cube shears sideways by an amount w as shown in Fig. 1.7, the shear strain is:

$$\gamma = \frac{w}{l} = \tan\theta \simeq \theta \tag{1.6}$$

If the deformation is small, $\tan\theta \simeq \theta$.

Stress: σ, [$ML^{-1}T^{-2}$], Pa, kPa, MPa. When a force (F) is applied to a cylinder of material in tension or compression, it is said to be in a state of stress. It is calculated by the force applied to the cylinder divided by the area (A) of a section perpendicular to the direction of the force at any moment of the deformation. Why is this said? Where the stress–strain curve starts leveling off (ductility zone), one is seeing a reduction of section somewhere halfway between both ends, the so-called *necking* as shown in Fig. 1.6. If the actual section at any moment of the curve is not taken into account, the stress is called *engineering stress*. In that case the curve will go through a maximum before fracture.

Thermal expansion coefficient: α, [T^{-1}], °C^{-1} (usually $\times 10^6$). The linear expansion coefficient is the ratio of the change of length per degree C to the length. It is only approximately linear in function of temperature range. The volume expansion coefficient is roughly three times the linear coefficient.

Yield strength: YS, [$ML^{-1}T^{-2}$], Pa, kPa, MPa, Nmm^{-2}. Tensile yield is a given value of stress where the stress–strain curve departs from linearity. From this value on a permanent set or deformation remains after removal of stress. For practical reasons, the stress inducing a plastic deformation of 0.2% is generally taken as the yield strength.

Ultimate tensile strength: UTS, [$ML^{-1}T^{-2}$], Pa, kPa, MPa, Nmm^{-2}. It is the highest endurable stress at which the test specimen begins to neck in tensile or to fracture (mainly for brittle materials) in compression.

Viscosity (dynamic): η or μ, [$ML^{-1}T^{-1}$], Pa s or kg/s m. It is a measure of the resistance of a fluid which is being deformed by either shear stress or extensional stress (see Sect. 2.3.1).

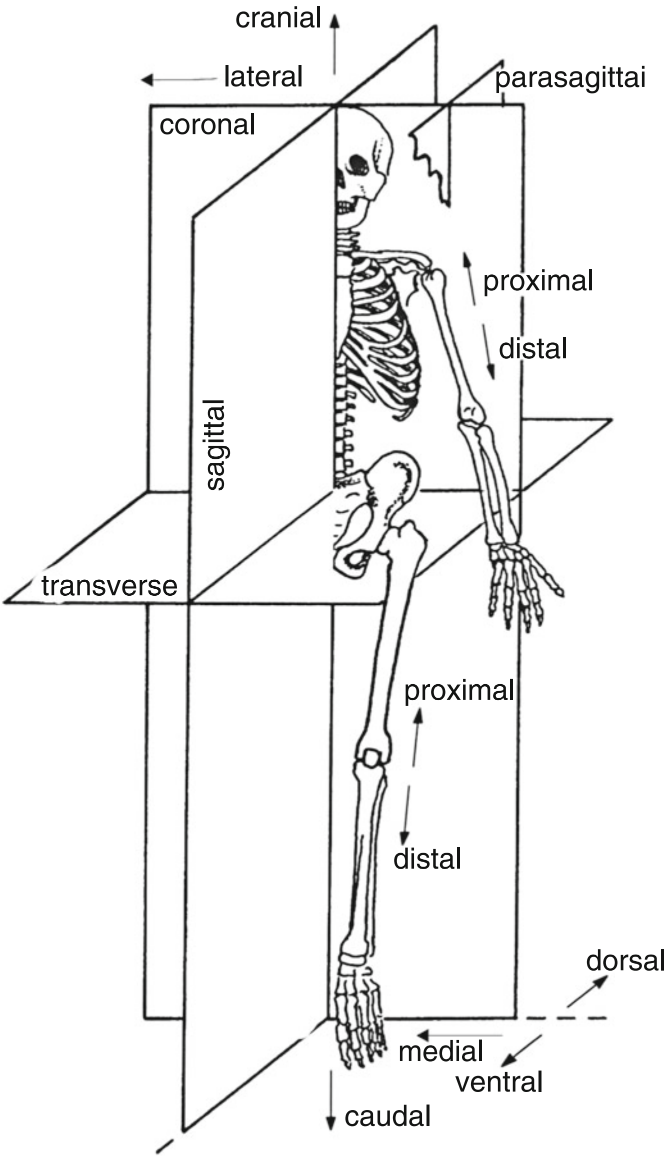
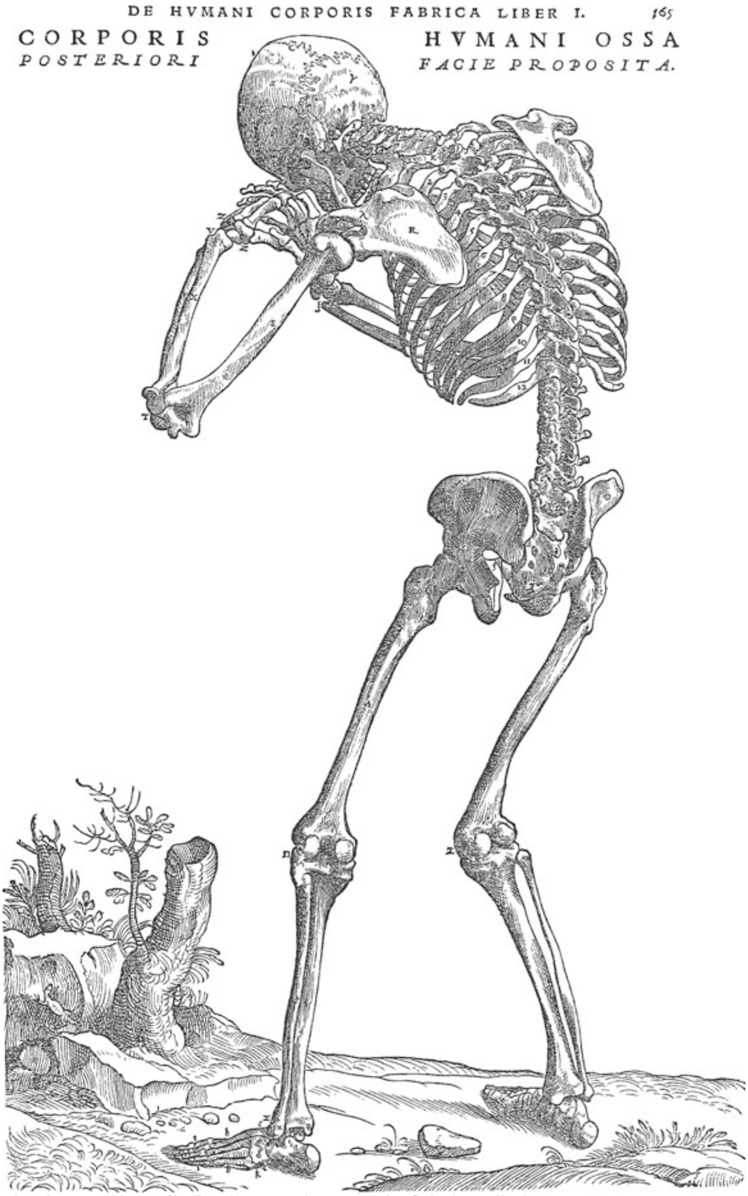


Fig. 1.8 Most common terms relative to skeletal anatomy. Adapted from [40], Fig. 1.1. Reproduced by permission of Springer Verlag

For a more in-depth treatment of mechanical properties, the reader is advised to consult current textbooks (Ashby, Timoshenko, Allen and Thomas or French [36–39]).

Anatomical terms: the most common terms are relative to the skeletal anatomy and are illustrated in Fig. 1.8.

In this chapter, the content of the book is introduced projected against a philosophical background. Prior to human implantation, implants are developed and tested in smaller animals and are subsequently upscaled for human use. Therefore, a discussion was devoted in Sect. 1.2 to scaling laws because upscaling is not a linear process, supplemented with some thoughts on data handling and data reduction. In Sect. 1.3, definitions are given of common mechanical properties figuring throughout the book.



Andreae Vesalii: De humani corporis fabrica libri septem
Basileae: ex officina Joannis Oporini, 1543

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