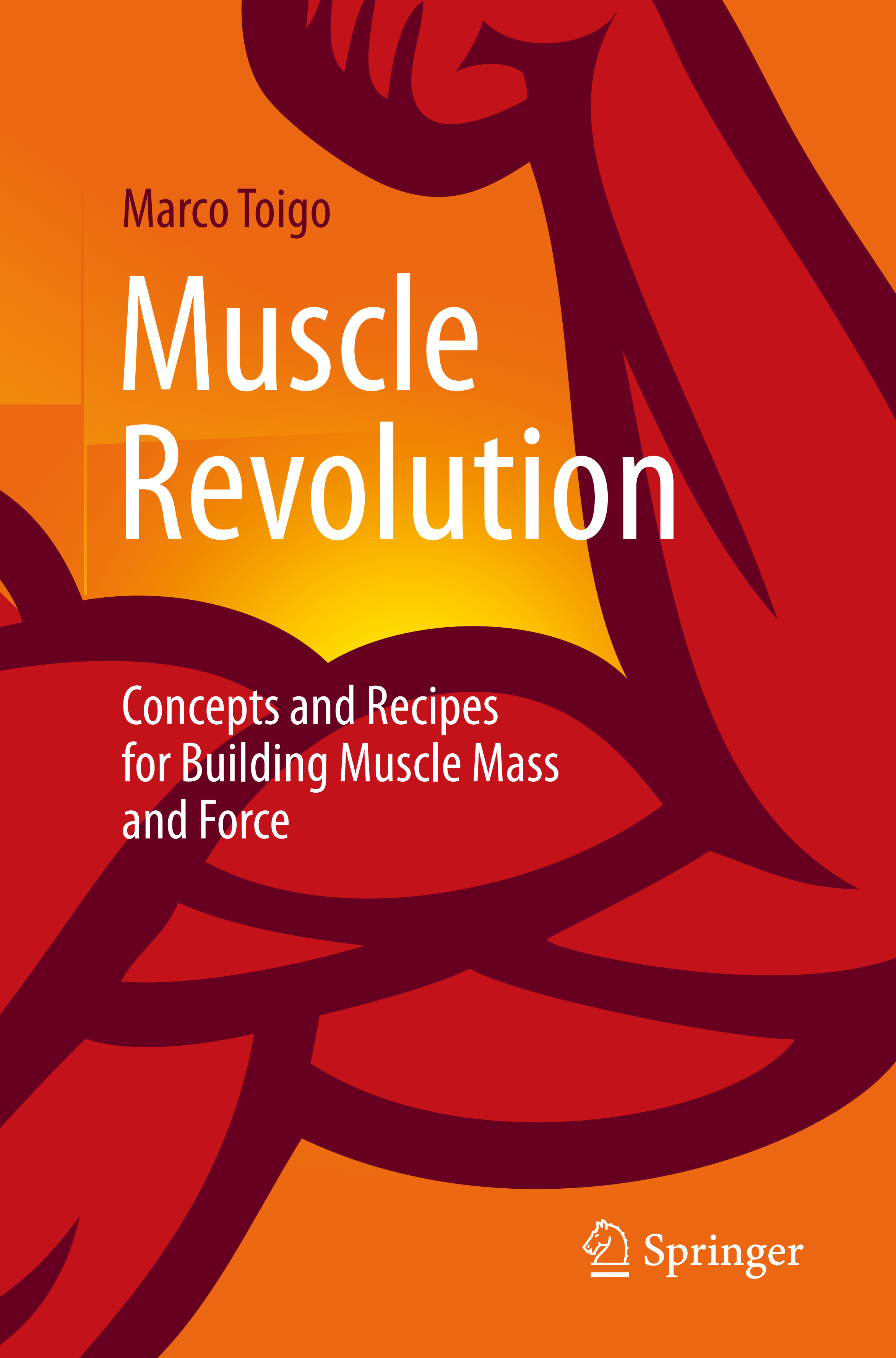

Marco Toigo

Muscle Revolution

Concepts and Recipes for Building Muscle Mass and Force

Springer

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Marco Toigo PhD
Zürich, Switzerland

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Foreword

In practically every magazine you will find tips and recommendations from "experts" on how to train effectively and efficiently and on optimal nutrition. In bookstores, books on strength and fitness training fill entire shelves and departments. Television is also teeming with relevant messages and the Internet represents a veritable jungle of information in this regard. How is a normal person who wants to find out about training and nutrition supposed to find his way through this swamp of opinions? Because this much is clear: There are not nearly as many scientifically proven facts on the subject of training and nutrition as there are training recommendations and so-called training systems.

To find your way through the jungle of training and nutrition opinions and to sharpen your eye for the essentials, there is only one thing to do: acquire the necessary expertise. All you need is understandable, quality-controlled information. The source of quality-controlled expert information is all *peer-reviewed published* literature (literature that has been peer-reviewed by independent experts prior to publication) from a wide variety of disciplines in the natural sciences of muscle research, such as muscle physiology, molecular and cell biology, genetics, neuroscience, nutritional science, and biomechanics. Only by integrating the different scientific perspectives and findings and comparing them with training practice does an overall picture emerge from which conclusions can be drawn as to what is sensible or proportionate in terms of training and nutrition.

In this book, I try to build a logical and robust bridge between this scientific knowledge and training and nutrition practice. I know at this point there would normally come a point where the author subtly signals his expert status to you so that you believe what is in the book. This is usually done by communicating status symbols, that is, a list of scientific awards, athletic accomplishments, years of experience, or simply muscular looks. You won't find that bling-bling here. I prefer to let hard facts speak for themselves.

MarcYigo PhD

Instructions for Use of This Book

The book consists of the following five elements: Main Text, Summaries, Info Boxes ("Knowledge Drops"), Illustrations, and Bibliography. The boxes, which are distributed throughout the book, aim to answer widely asked questions briefly and clearly. The bibliography provides the precise details of any academic papers, books, or websites cited in the text. The illustrations and diagrams are intended to help illustrate textual content and thereby make it more understandable, or to provide another approach. The main text is divided into 24 chapters, all of which provide a very deep, yet practical insight into the nature (science) of skeletal muscle and its malleability through Resistance Training.

In this book you have several access modes and content difficulty levels at your disposal. This allows you to approach the content according to your previous knowledge and interests. For example, in the boxes you will quickly get well-founded answers to your questions without first having to rummage through countless pages. Starting from these boxes, you can go into more detail in the relevant chapters, or you can jump in at any chapter and explore the rest of the content from there, thanks to the cross-references. The summaries reflect the presented contents in a concise form and sometimes show the practical relevance with concrete tips. Finally, you can also use the book as a classic textbook and reference work.

The first third (Chaps. 1, 2, 3, 4, 5, 6, 7, and 8) of the book deals mainly with basic muscle physiology. This can seem a bit dry at times, but is no less important. Hang in there! You will be rewarded with enlightening and unexpected insights. We then turn to the peculiarities and laws of voluntary muscle (fiber) use in Resistance Training and explore how you can specifically influence skeletal muscle development and strength through training and nutrition. The focus is always on the transfer of scientific findings into everyday training.

I hope that you will benefit from this book by understanding, first and foremost, how Resistance Training, nutrition, and muscle adaptation interact based on individual prerequisites, and what the practical consequences are for your training and nutritional habits. I wish you an interesting and satisfying journey into the wonderful world of muscle training!

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1

What Are We Talking About? Clear Thinking Through Clear Terminology and Vice Versa

1.1 Muscles Contract: Not (Only)!

What is the first thing that comes to mind when you hear the commonly known term “muscle contraction”? Well, I don’t have to be psychic to guess that you automatically think of the contraction or shortening of the muscle. This is not surprising at all. Even the definition in the *Duden foreign dictionary* is “(Med.) the contracting (esp. of muscles)”. Unfortunately, this definition is woefully inadequate to describe muscle function and misleads us into misconceptions. Why?

Imagine you are standing upright, your arms are hanging by your sides and you are holding a dumbbell in your right hand. Experience shows that you can move the selected dumbbell mass up and down several times without difficulty. Now bring the dumbbell to your chin, just as you would bring an apple to your mouth. What happens during this bending movement? When lifting (pulling) the dumbbell, the arm flexor muscles, among others, produce force while the forearm bones, to which the muscles are attached by tendons, approach the humerus and shoulder blade. From the outside, the muscles shorten and the angle between the upper and lower arm becomes smaller. So how does the dumbbell get back to the starting position? In this case, you can do this by deliberately reducing the force applied. This reduces the muscular torque compared to the external torque – the dumbbell moves back to the starting position as a result. When lowering (braking), the arm flexor muscles therefore also generate force, but they become longer on the outside and the angle between the upper and lower arm increases. If you pause briefly at the

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reversal points between flexion and extension (or *vice versa*) while holding against the dumbbell, no movement is visible from the outside, but your muscles are still generating force continuously.

But there is a second way, how you can bring the dumbbell to the starting position (stretched arms to the side of the body, hands to the side of the hips). To do this, imagine that you – attached by your feet – hang upside down on a horizontal bar, still holding the dumbbell with a bent forearm to the chin. In this case, you get to the starting position by having the opposite muscles (the so-called antagonists) of the arm flexors, the arm extensor muscles, move the dumbbell back by extending at the elbow joint. In the process, mainly the arm extensor muscles produce force, and shorten (external view). As a result, the angle between the upper and lower arm increases. The intended effect of some muscles, for example the arm flexors, is therefore to reduce the angle between the upper and lower arm (angle of the elbow joint). For other muscles, such as the arm extensors, this is exactly the opposite.

What do we learn from these observations? The muscles *try to* shorten, but the shortening is not necessarily the result. Depending on the amount of force produced and the amount of force to be overcome, the result can also be a relative lengthening or no change in length (always viewed from the outside, of course). Equating muscle contraction with muscle shortening therefore falls far short of the mark. If you concentrate exclusively on the muscle-shortening movement phase when training your muscles, because you think or have been told that your muscles only work in this movement phase, you neglect the other forms of use that are just as important for training success. Furthermore, you are ignoring the fact that it is precisely the aspect of neural activation and force production (regardless of the direction of length change) that is central to training adaptations. And if muscle contraction is supposed to equal muscle shortening, how please should the commonly used term combination "isometric muscle contraction" be understood? Exactly. Not at all, because "isometric" – "iso-" (gr. ísos for similar, corresponding, equal) and "-metric" (referring to the meter as a unit of length) – means something like "equal length", which contradicts muscle contraction if it is understood as muscle shortening.

Box 1.1: Quintessence: What Is "Functional Training" Really?

Skeletal muscles are essential for the function of our organism and thus for our health. They fulfil several important tasks. In the context of human movement, the actual function of skeletal muscles is to produce force (see Sect. 1.15). In doing so, the muscle tries to shorten itself, which it often does in everyday life. For example, when you bring an apple to your mouth, your biceps muscle shortens. However, muscle shortening is not always the result of force production. In other words, externally visible limb movement is not necessarily the result of muscle force generation. You will become aware of this fact as soon as you try to lift a tank with maximum effort. It will not budge even though your muscles are generating a lot of force. Similarly, when holding or carrying shopping bags, your shoulder and neck muscles produce force even though the shopping bags remain more or less at the same height. Finally, in everyday life it often happens that you have to slow down movement, for example when walking or going down stairs. After you put your foot down, the knee bends and the thigh muscles produce force to prevent you from buckling. In this case, the muscles produce force while they are stretched a bit. From these observations, it is clear what "functional" really means for a muscle: it is stimulated voluntarily or reflexively by nerve impulses and produces force. Whether a movement is externally visible and how fast this movement is, depends primarily on the amount of muscle force produced relative to the force imposed by the external load and the lever arm. Muscle force characteristics in turn depend on neural and muscular factors, namely the recruitment and firing frequency of motor units and the structural and metabolic properties of their muscle fibers. In this sense, your training is automatically "functional" once your muscles are neurally stimulated and producing force. However, the target of a muscle's force production (shortening) can vary because a single muscle can normally perform multiple movement tasks. For example, the biceps muscle not only has the task of flexing the elbow, but also of rotating the wrist outward or lifting the arm forward when the elbow is flexed. From this perspective, training becomes more functional when you train a specific muscle in all of its movement tasks. In resistance training, this means that you should work the different anatomical-neuromuscular compartments of a muscle, *nota bene* if they exist, with several, functionally different exercises. This increases the chance that the training effects will also be effective in your sport or during everyday activities. In other words, it increases the transfer effect of resistance training. One thing is clear: there is no convincing scientific basis for claims that single-joint exercises are less functional than multi-joint exercises.

1.2 Mice Under the Skin

Incidentally, etymologically the term "muscle" can be derived from the Latin word *musculus* (little mouse), because the image of shortening muscles resembles the idea of mice running under the skin. Historically, the first attempts to explain how muscles work date to the Greek physician Hippocrates (460–377 BC). However, it was Galen (129–216 AD), a physician from Pergamon (now Bergama, Turkey), who attempted to explain muscle function mechanistically. Among other things, he postulated that there was a substance in the brain (lat. *spiritus animalis*) that was able to flow through the nerves, which were imagined to be hollow, into the muscles and expand them. This, according to his conception, would activate the muscles. This theory was so pervasive that it lasted into the seventeenth century. It was not until 1663 that Swammerdam showed, by means of an elegant neurophysiological experiment, that an isolated muscle does not increase its volume when stimulated. This experimentally disproved Galen's theory. Apparently, however, the equally clear result was overlooked that stimulation also does not lead to a reduction in volume (i.e. volume contraction) of the isolated muscle. Nevertheless, to this day the inappropriate expression of muscle contraction can stubbornly persist. But you know better now: instead of "contraction", just use "force production"!

1.3 Why Skeletal Muscles Do Not Have Eccentric Airs and Graces

Besides "isometric", the two adjectives "concentric" and "eccentric" are also very often combined with the noun "muscle contraction", only these two adjectives are even more meaningless in the context of skeletal muscle activity than the aforementioned "muscle contraction". "Concentric" means something like "having a common center" (referring to circles) while "eccentric" can be translated as "lying outside the center (of circles)." While these two geometric terms are compatible with the physiological or pathological adaptations of the heart muscle, or ventricles, they do not make sense in the context of heart muscle and skeletal muscle function. Even if a cardiac enlargement is eccentric in nature (e.g., a left ventricular only cardiac enlargement) and the cardiac muscle then produces force under eccentric conditions, in the process the muscle fibers become progressively shorter, remain the same length, or are stretched under special circumstances. The further meaning of "eccentric" as "unusual in an exaggerated way", then makes the term combination "eccentric contraction" finally a curiosity.

You may wonder why I keep emphasizing the outside view. The answer is: because quite different processes can be going on inside. The many muscle fibers (i.e., the multinucleated muscle cells) are organized in bundles (fascicles) and embedded in a network of connective tissue, commonly called the extracellular matrix. Externally, the muscle is surrounded by a layer of coarse connective tissue (muscle fascia). Muscle fibers and extracellular matrix are connected to tendons via the muscle-tendon junction, which in turn is the link to bone. In this context, one speaks of the muscle-tendon unit (Fig. 1.1).

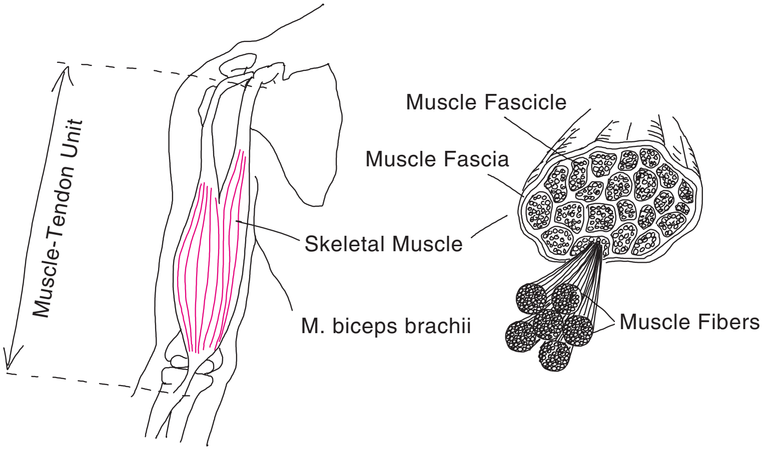

Fig. 1.1 Muscle-tendon unit and structure of skeletal muscle. Note that under given circumstances the length of the muscle-tendon unit may increase with simultaneous muscle shortening. Therefore, the length of the muscle-tendon unit is not the same as the muscle length. A skeletal muscle consists of many bundles of individual muscle fibers (fascicles)

1.4 Do Not Be Deceived by Appearances

When viewed from the outside, for example in the case of the arm flexor muscles, the joint angle between the upper and lower arm becomes smaller, one speaks of the muscle shortening. Strictly speaking, however, it is the muscle-tendon unit that shortens and not necessarily the muscle or the muscle fascicles in all cases. How so? Think of the two-legged jump. You can initiate this jump from a standing position. In doing so, you swing your arms and simultaneously bend your knees (squatting motion), and then immediately shoot up into the air. This is called a *countermovement jump*. By definition, such countermovements involve a stretch-shortening cycle, in this case for the knee extensor muscles. It is typical for stretch-shortening cycles that, due to the higher preload at the beginning of the shortening of the muscle-tendon unit (*i.e.* at the end of the lowering movement in the squat), the tendon stretch is greater than the fascicle stretch. This means that the fascicles of the knee extensor muscles shorten before any movement occurs in the knee joint (*i.e.*, the muscle-tendon unit does not change length during this phase). During the jump, the fascicle length then remains relatively constant while the tendons snap back at high speed (the muscle-tendon unit becomes shorter). If the muscles had to shorten at high speed in order to perform the jumping movement, muscle force would be low (see Sect. 1.6).

The rapid shortening of the muscle-tendon unit therefore depends primarily on the shortening of the tendon during stretch-shortening cycles. In contrast, the shortening of the muscle-tendon unit of the knee extensor muscles in movements without a stretch-shortening cycle, for example in a two-legged jump without a countermovement (i.e. starting in a squat position), is primarily due to the shortening of the muscle fascicles (more or less constant tendon length; Cormie et al. 2011). At the same time, during this type of jump, the calf muscles (specifically the medial head of the twin calf muscle, M. gastrocnemius medialis) behave like the thigh muscles during the jump with stretch-shortening cycle. The Achilles tendon plays an important role in connection with energy storage and release.

As I have just explained to you, the term "muscle contraction" as well as the adjectives "concentric" and "eccentric" used with it are inadequate or incorrect to describe muscle function. What is needed is an unambiguous and correct nomenclature. In English, the problem has been solved by simply using the adjectives shortening, lengthening or *isometric* before muscle *action*. This way you are describing the result of muscle function. The function of the muscle is, as mentioned before, to produce force. In doing so, it attempts to shorten.

1.5 The "Trinity" of Force Production

As early as 1938, Hubbard and Stetson recognized that muscles can perform their function under three conditions. They called these three conditions "miometric", "isometric" and "pliometric" (Hubbard and Stetson 1938). These adjectives are composed of the Greek prefixes "mio-" (shorter), "iso-" (equal), and "plio-" (longer) and the word "-metric" and accurately sum up the result of force action or force application on the length of the muscle-tendon unit. For the rest of the book, therefore, instead of "concentric, isometric, eccentric contraction," I will speak of "miometric, isometric, pliometric force production."

How can you remember which change in length "miometric" and "pliometric" stand for ("isometric" is already established in linguistic usage)? Quite simply, in the word "pliometric" the letter "l" occurs for "longer" or "long". Always be aware when reading that the adjectives are primarily describing the change in length of the muscle-tendon unit. The book will also frequently refer to muscle fibers. Consequently, in the context of individual muscle fibers or muscle fiber bundles, the adjectives refer to the length of these structures. Finally, note that the adjective "pliometric" used here should not be confused with "plyometric training". The latter is colloquially used to describe jump training.

1.6 The Relationship Between the Rate of Change of Length and the Force of a Muscle

On the one hand, the force-velocity relationship (Hill 1922; Katz 1939; Fig. 1.2) describes the fact that a muscle produces less force with increasing shortening velocity. Conversely, this means that a muscle can only produce a large force when shortened if the shortening velocity is low. You know this from your daily experience: a pencil (low load, little muscle force) can be moved faster than a tree trunk (high load, much muscle force), even if in both cases you try to move the resistance as fast as possible. On the other hand, the force-velocity relationship describes that at negative shortening velocity, i.e. stretching, increasingly more force is produced as the stretching velocity increases until it reaches a plateau, and more than isometrically possible. You are also familiar with this phenomenon from practice. When you lower the dumbbell each time in training (braking part of the movement or negative shortening speed), the load feels lighter because the muscle is stronger in this force production mode. The amount of muscle force generated therefore

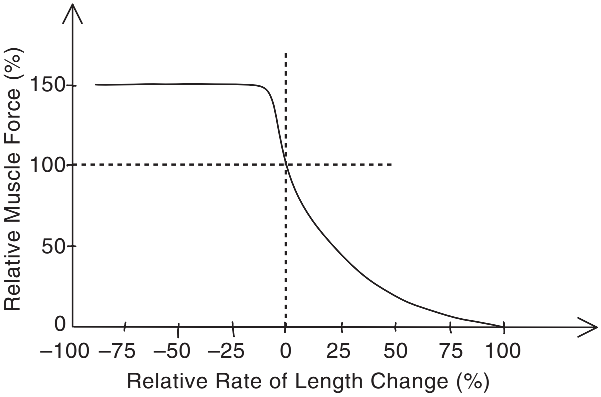

Fig. 1.2 Force-velocity relationship for a skeletal muscle. Note that when the rate of length change is negative (i.e., pliometric activity), muscle force increases rapidly at first, then does not change as it progresses, and decreases sharply as the rate of shortening increases (positive) (i.e., miometric activity). Muscle force production with a shortening speed of zero is referred to as isometric muscle activity

depends on the speed of the change in length of the muscle, but this in two respects: direction and amount.

Direction

By convention, during force production with muscle shortening, the velocity is positive, while during force production with muscle stretching, it is negative. Incidentally, terms such as “positive or negative phase of movement” and “negative training” are derived from this. When the rate of change in length is zero, force production takes place isometrically.

Amount

During miometric force production, you can move the physical body being moved faster if its weight force is small relative to the instantaneously available peak voluntary force. During pliometric force production, the rate of change in length (in this case, elongation) is greater when the object’s weight force is large relative to the instantaneously available peak voluntary force. In other words, the heavier the dumbbell for a given muscle force, or the more fatigued your muscle is for a given external load, the faster the braking phase.

Box 1.2: What Can You Deduce for Your Training from the Described Force-Velocity Relationship?

You can deduce two things: First, when miometric force production is fast, the muscle force produced is relatively small. Conversely, the slower the rate of shortening, the more force the muscle can produce. Assuming that high internal forces can be beneficial for muscle strengthening during training, the training load should be moved slowly during muscle shortening. Second, muscle force is always greater at maximal activation during pliometric force production (regardless of stretch speed) than during isometric or miometric force production. Try to move slowly at all times during training, even if that is not always the visible result.

As an example, I describe here the performance of negative pull-ups (negative training). If you can do less than four anatomically perfect and slowly executed pull-ups, a pull-up bar and a small staircase are completely sufficient for this experiment. Climb the stairs and hold onto the bar with an underhand grip so that your chin is higher than the bar when your neck is straight, and your forearm, upper arm, and shoulder are in the same plane on each side. Now angle your lower legs and cross your feet while still holding firmly in the starting position. You are now literally hanging in the air. Now try to slow down the downward movement of your body evenly and slowly (in about 10 s). Do not let go of the bar when you reach the bottom and immediately and quickly climb back up the stairs to the starting position. Repeat the braking process. You will notice that as you brake more and more (i.e., repetitions), the downward motion becomes faster and faster, even though you are using maximum voluntary effort to try to slow your body down. After a few repetitions you will virtually free-fall, i.e. in less than 1 s – this point in time then corresponds to the end of the exercise.

1.7 What Does "Exercise" Actually Mean and How Is It Quantified?

Now that we have clarified the movement function of muscles, we are in a better position to examine the meaning of the term "exercise". *Exercise* is the potential disruption of homeostasis by muscle activity that is either exclusively or in combination miometric, isometric or pliometric in nature. This definition takes into account that, on the one hand, disruption of metabolic processes is likely, but that, on the other hand, movement may not necessarily be a result. Moreover, the definition can be applied to all situations and all muscles (cardiac muscles, smooth muscles and skeletal muscles). Incidentally, this definition is also applicable to the term "physical activity". The difference between exercise and physical activity is therefore the different context of muscle activity and the related different interpretation of the motivation or intention of the individual.

The next question is how to quantify training. The answer to this question can be found in the International System of Units (*Système International d'Unités*, SI). The SI was introduced in 1960 as the twelfth resolution of the eleventh General Assembly on weights and measures. It is administered by the *International Bureau of Weights and Measures* (http://www.bipm.org), which publishes the SI reference booklet every few years. This sets out the internationally recognised quantities, units and symbols that apply to all measurements. In science, following the SI is mandatory, because it is the only way to compare measurement results from different (laboratory) corners of the world. In training practice, one should at least be able to distinguish which terms are SI-compliant and which do not make sense.

1.8 If You Want to Lose Weight, Fly to the Moon!

As I said, one important function of muscles is to exert force. Of course, muscles also perform other fundamental functions for our survival, which I will discuss later. But what is force anyway? In 1687 Isaac Newton published his work *Philosophia Naturalis Principia Mathematica* (Mathematical Principles of Natural Philosophy). In it, he formulated three principles or laws of motion. The concept of force comes from the first of Newton's three laws, the law of inertia. It states, in simple terms, the following: Force is that which acts to change the state of rest or the uniform rectilinear state of motion (*i.e.*, motion with constant velocity and no change in direction). The SI unit of force is the newton (N). Thus, in the case of linear motion, that is, motion along a straight line, a force applied to a stationary or moving object tends to accelerate the object. The "reluctance" or inertia of the object to change its state is due to its mass.

The SI unit for mass is the kilogram (kg). Due to the effect of gravity, mass exerts a force and this force corresponds to the weight of the object. The two quantities "weight" and "mass" are often not distinguished from each other, especially when it comes to our body properties. Body weight is a force and should therefore be expressed in newtons, whereas body mass should be expressed in kilograms. If your body mass is 80 kg, then your body weight on earth is approximately 800 N. If you want to lose body weight, fly to the moon. There you will weigh about six times less than on Earth. Joking aside, it is more likely that you want to lose fat mass and gain muscle mass, and I hope the contents of my book can help you do that.

1.9 Muscles Only Want One Thing: To Rotate Loads Around Joints

However, especially in the context of training, we are not primarily interested in the linear effects of force, but rather the angular effects. If you bring an apple to your mouth with one hand, the hand rotates around the elbow joint, i.e. the apple moves circularly and not linearly around the elbow joint. Even if you move an object more or less along a line (for example, when pressing a dumbbell up), the straight-line motion of the dumbbell comes only from simultaneous rotation of the humerus at the shoulder joint and the forearm bones at the elbow joint. Consequently, the action of a muscle manifests itself as a torque around the corresponding joint rather than as a linear force. The reluctance of the body to change its angular motion is called the moment of inertia. The moment of inertia, in turn, depends on the mass of the physical body and the distribution of that mass about the axis of rotation. The muscular torque is calculated from the vector cross product between the moment arm and the acting force. The moment arm, in turn, represents the magnitude of the muscle force component perpendicular to the joint's center of rotation, while the lever arm corresponds to the distance between the joint's center and the point of force application on the bone being moved (in the example of the biceps brachii muscle, the two-headed arm muscle, this corresponds to the tendon attachment point on the forearm bone). Simply put, the moment arm is the distance perpendicular to the line of action of the muscle force from the line of action to the pivot point (joint).

The SI unit of torque is the newton metre (Nm). Muscular torque opposes the torque generated by the external force (Fig. 1.3). Thus, if you are holding a dumbbell in your hand, the external torque is equal to the product of the magnitude of the weight force component of the dumbbell acting *perpendicular to* the forearm and the distance of the dumbbell from the center of the elbow joint. Roughly speaking, this distance is equal to the length of your

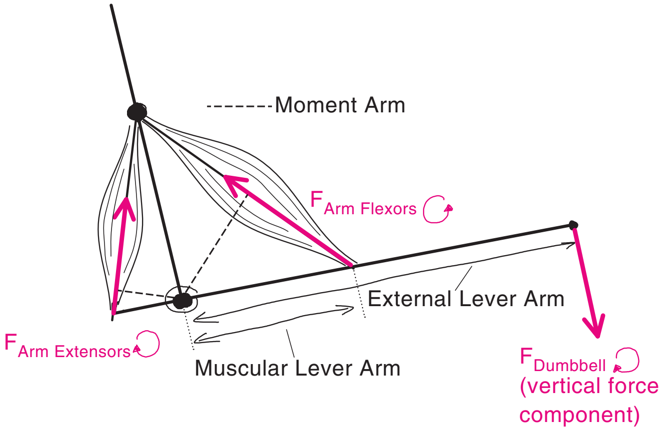

Fig. 1.3 Forces acting during a biceps curl with a dumbbell. The muscle-tendon unit of the arm flexors shortens (miometric force production) only if the muscular torque (product of the magnitude of the moment arm and the muscular lever arm) of the arm flexors is greater than the sum of the torques caused by the training resistance (dumbbell) as well as the arm extensor muscles. The external torque is equal to the product of the amount of the weight force component of the dumbbell perpendicular to the forearm and the external lever arm

forearm bone. From these considerations it becomes clear why you feel the most resistance during the lifting of a dumbbell (bending at the elbow joint) in that joint position where the forearm bone is horizontal to the surface of the earth: At that position, the weight force of the dumbbell acts exclusively perpendicular to the forearm bone. If the muscular torque of a muscle (e.g. the arm flexor muscle, M. brachialis) is greater than the external torque and also greater than the torque of the antagonist muscle (in this case the arm extensor, M. triceps brachii), the resulting muscle action is miometric in nature. In the opposite case, the muscle action is pliometric. If the opposing torques are in balance, there is no externally visible movement (isometric case).

1.10 Why Your Muscles (Have to) Work Even Though You Are Not Performing Any Work

If the point of application of a force moves in such a way that the direction of movement is wholly or partially in line with the direction of the force, mechanical work is performed. Consequently, mechanical work is calculated from the product of force times distance (displacement). But beware! Mechanical work is only done (i.e. the sign of the work is positive) if the distance travelled is opposite to the direction of the force. The SI unit for distance is the metre (m). Mechanical work is thus given by the product newton times meter (Nm), which corresponds to the SI unit joule (J). In the context of exercise, however, the concept of mechanical work should be taken with a grain of salt. Think of isometric muscle force production. For example, if you are standing upright holding a heavy bag steady, your trapezius muscles are producing a lot of force, but the external mechanical work done is zero because your hands are not moving.

In principle, therefore, exercise must not be equated with the performance of external mechanical work. In addition, when using the term mechanical work, the energetic or thermodynamic system must always be specified. Indeed, in the case of a movement, the whole body or only individual limbs or segments can be considered as a system. The mechanical work performed then corresponds to the net change in the energy of the defined system. In the context of exercise, one therefore distinguishes internal and external work. Consider the following case. There is a very heavy dumbbell on your desk and you try to lift it with maximum effort. However, you do not even begin to succeed – the use of the muscle-tendon unit is consequently isometric. What happens inside the muscle? The muscle fibers shorten, while the elastic components of the extracellular matrix and the tendons stretch to their limit. Strictly speaking, the muscle (or the muscle fibers) is doing mechanical work. This can be called internal work. Nevertheless, the external mechanical work remains zero. The term “internal” can also be used to refer to the mechanical work that must be done simply to move one or more parts of the body, regardless of whether external work is being done. Think of leg movements while riding a bicycle and now imagine that you are mimicking them on a stationary bike without pedals. The external mechanical work is zero in this case. But you do have to do (internal) mechanical work to move your legs at all.

1.11 What Do Human Muscles Have to Do with Horses?

The rate at which mechanical work is performed is called power. Power is also a construct from classical mechanics. Historically, the use of this mechanical quantity can be traced back to the Scottish inventor James Watt (1736–1819). Based on the design of Thomas Newcomen (1663–1729), Watt further developed the steam engine by improving its efficiency. At the time (the beginning of the Industrial Revolution), industrial processes were powered by horses. Watt therefore proposed to quantify the effectiveness of steam engines relative to that of horses. Hence the term *horsepower* coined by Watt. The SI unit of power is the watt (W). One watt is equal to one joule per second (Js^{-1}). So what is energy? Energy manifests itself in different forms, for example in heat, light, electricity, chemical reactions, sound and, of course, motion. In the case of motion, we speak of kinetic energy. Forms of energy can be converted into each other. For example, ingested food is digested, including converting complex insoluble material into simple soluble substances. These soluble substances can then be transported in the body and absorbed by body cells.

Conversely, metabolic intermediates (metabolites) can also be transported from the cells by the blood and taken up by other cells or excreted via respiration or urine. When an enzyme (a molecule, usually a protein, which has a catalytic effect) interacts with a substance, the substance is called a “substrate”. During the interaction between substrate and enzyme, energy can be released, but often energy is invested. The energy currency in our cells is adenosine triphosphate (ATP). During exercise, ATP provides the chemical energy for muscle fibers to produce force, – and when movement occurs in the process, to convert chemical energy into kinetic energy. A change in energy means that