Correlation of Skeletal Muscle Anatomy to MRI and US Findings

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Contents

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Abstract
Muscles are anatomical structures with the capability to reduce their length if stimulated appropriately. In this chapter the anatomy of the skeletal muscle and of its imaging appearance are briefly reviewed. The anatomic description starts from the microscopical anatomy to reach the macroscopical anatomy. Biomechanical principles of levers and muscular contraction are also reviewed. Imaging features are described with an emphasis on ultrasound and magnetic resonance imaging. Moreover, a brief overview on accessory muscles is presented.

1 Key Points

1. The muscles are anatomical structures with the capability to reduce their length if stimulated appropriately.
2. According to the famous anatomist of the past Bichat, muscles are divided into two main groups: muscles of animal life and muscles of vegetative life. The first group is characterized by the capability to react under one person's will, and their contraction is quite fast. The other group, the "visceral muscles" are not dependent on the will of the individual.
3. Microscopical anatomy: the smallest contractile unit of the skeletal muscle is the muscle fiber or myofiber, which is a long cylindrical cell that contains multiple nuclei, several mitochondria, and sarcomeres.
4. Muscle fibers classification: individual muscle fibers are classified by their histologic appearance and by their ability to use energy deposits.
5. Classification based on the relationship between muscle and tendon: considering the relationship between the muscle and the tendon, the muscle may be divided into those having a direct insertion and those having a lateral

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insertion, or according to its general shape and predominant orientation of fibers.
6. Ultrasound, magnetic resonance imaging and computed tomography are widely used with different purposes to visualize the normal anatomy of the musculoskeletal system.
7. Anatomical variants: muscular anatomical variants are more common than normally thought. Muscular anatomical variants include not only supernumerary or accessory muscles, but also their absence, their deviation from a normal course, and an anomalous origin or insertion.

2 Introduction

Muscles are anatomical structures with the capability to reduce their length if stimulated appropriately. According to Bichat, the famous anatomist of the past, they are divided into two main groups: muscles of animal life and muscles of vegetative life. The first group is characterized by the capability to react under a person's will, and their contraction is quite fast. The other group, the "visceral muscles" are not dependent on the will of the individual. The muscles of animal life are characterized by several fibers which are arranged in "striae." For this reason the term "striated muscle" may be used to describe the muscles of animal life, or also called voluntarily controlled. The term "striated muscle" is sometimes used to describe the cardiac muscle.

3 Microscopical Anatomy

The smallest contractile unit of the skeletal muscle is the muscle fiber or myofiber, which is a long cylindrical cell that contains multiple nuclei, several mitochondria, and a lot of sarcomeres (Boron and Boulpaep 2009). Muscle fibers are long and cylindrical and they range in size from 10 to 100 μm. In general, larger fibers are found in big and powerful muscles such as the muscles of the thigh. However, fibres are small in muscles which have the task to perform quick and precise movements, such as the extrinsic muscles of the eye. The functional subunit of the muscle fiber is called sarcomere. Sarcomeres contain two types of protein filaments: a thick filament (myosin) and a thin filament (actin, troponin and tropomyosin). The movement of these filaments with respect to each other guarantees movement.

Microscopically, a muscle fiber presents transversely orientated bands called Z-lines which constitute the limits of the sarcomere. In classical textbooks they are also described as A-bands and I-bands. The A-bands consist of thick filaments with interdigitation; the I-bands consist of two adjacent sarcomeres with no interdigitation. A more detailed description of these bands is beyond the scope of this chapter. Muscle fibers have multiple nuclei and adjacent to the myofibrils there are the Golgi apparatus, the ribosomes, and the mitochondria in sufficient numbers, which depend on the main function of the muscle (prevalence of aerobic or anaerobic metabolism). A single muscle fiber is surrounded by a thin layer of connective tissue named endomysium. Approximately a number, ranging from 20 to 80, of these muscle fibers are grouped together in a parallel arrangement. These groups of fibers form a muscle fascicle or fiber bundle. A muscle fascicle or a fiber bundle is encapsulated by another layer of connective tissue called the perimysium. The perimysium is thicker than the epimysium enclosing each of the bundled muscle fibers. A single distinct muscle is formed by a large number of muscle fascicles enveloped in a thick collagenous external sheath extending from the tendons called the epimysium (Korthuis 2011; Standrings 2005).

3.1 Muscle Fibers Classification

Individual muscle fibers are classified by their histologic appearance and by their ability to use energy deposits. Type I fibers are generally slow-twitch fibers, which are thinner, invested by a denser capillary network; on microscopy they are red due to the presence of a large amount of the oxygen-binding protein myoglobin. These fibers are resistant to fatigue, relying on oxidative metabolism for energy, and thus they have a high mitochondrial number and oxidative enzyme content opposed to a low glycogen presence and to a low glycolytic activity. On the other hand, type II fibers are fast-twitch fibers that differ among themselves with regard to resistance to fatigue. They are divided into type IIa and type IIb (Armstrong 1996). Type IIa muscle fibers contain abundant glycogen and more mitochondria to generate an adequate ATP content to balance the high rate of ATP hydrolysis. Type IIb fibers depend on glycogen storage and phosphocreatine: they contain few mitochondria, low content of myoglobin (for this reason they are called white muscles), and low levels of oxidative enzymes: for this reason type IIb muscle fibers are fast but easily fatigable. Type IIx, and 1–2 % type IIc fibers have also been described and they should be fast glycolytic fibers; they represent only 1 or 2 % of the total number of muscle fibers (Exeter and Connell 2010). Moreover, different muscle fibers receive different patterns of innervation by their motor neurons: the innervation pattern is different for different muscles. For example, the extrinsic muscles of the eyes have several motor units, whereas the powerful muscles of the back have a lower number of motor units with one motor neuron innervating a huge number of muscle fibers.

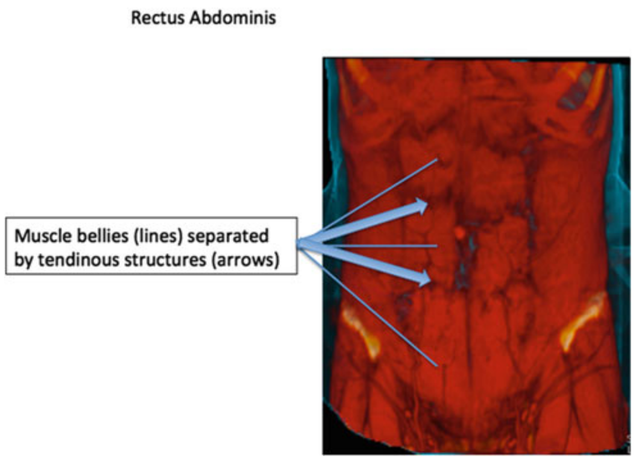

Fig. 1 Volume rendering computed tomography in false colors showing the macroscopical anatomy of the muscles of the abdominal wall, including the rectus abdominis muscle

4 Macroscopical Anatomy

Muscles can macroscopically be described and classified according to the following characteristics:

I. *Localization.* Muscles are divided into two big classes: superficial and deep, in relation to the position occupied regarding the superficial fascia.

II. *Number and mass.* It is difficult to count the total number of the muscles contained in the human body, because it is not clear how to classify a single muscular body. In the past the total number of muscles was reported to range from 346 by THEILE to 501 by SAPPEY. Their mass is approximately 3/7 of the entire human body.

III. *Classification based on the relationship between muscle and tendon*. Considering the relationship between the muscle and the tendon, the muscle may be divided into those having a direct insertion and those having a lateral insertion (Gray 2000), or according to its general shape and predominant orientation of fibers (Standring 2005).

The macroscopical shape and function of a skeletal muscle is determined by the internal arrangement of the fascicles.

Some muscles are strap-like (e.g., the sartorius muscle) and their fibers are parallel to the long axis of the muscle. The rectus abdominis muscle is a particular muscle where the muscle bellies are separated by tendinous structures oriented transversally (Fig. 1). Fusiform muscles, such as biceps, have fascicles that are orientated parallel to each other in the mid-portion, whereas at the end, near the myotendinous junction, the fibers converge. Pennate muscles have fascicles that are obliquely oriented relative to the line of traction. These muscles are called pennate because their aspect resembles a feather. From the biomechanical point of view these muscles contract against great loads (e.g., the soleus-gastrocnemius complex).

Pennate muscles include triangular-shaped (e.g., adductor longus), unipennate or semipennate (e.g., flexor pollicis longus), bipennate (e.g., rectus femoris), multipennate (e.g., deltoid), and circumpennate (e.g., tibialis anterior) muscles.

Some muscles are bipennate and their fascicles join a single central tendon; multipennate muscles have more than one tendon coursing through the muscle substance. Fascicles may also present a curved spiral arrangement between the origin and the insertion (e.g., pectoralis major, supinator). Several muscles are composed of a single belly or may have a complex internal architecture made up of multiple heads with a different origin (e.g., two heads for the biceps brachii and the biceps femoris; three heads for the triceps brachii and the triceps surae) and join together to generate a distal tendon (Fig. 2a–d).

From the biomechanical point of view, during muscle contraction, the force is transmitted to the skeleton by the tendon or aponeurosis and may or may not result in joint motion. Skeletal muscle contractions may be divided into three types: isometric, when the muscle contracts, but there is no change in its length; isotonic or concentric, when the muscle contracts and simultaneously shortens; and eccentric, when the muscle contracts and at the same time lengthens.

When a muscle is activated by the nervous system and it is required to lift a load which is less than the maximum tetanic tension the muscle can generate, the muscle is able to shorten. Contractions that permit the muscle to shorten are referred to as concentric or isotonic contractions. An example of a concentric contraction is the lifting of a weight during a biceps curl. In concentric contractions, the force generated by the muscle is always less than the muscle's maximum force. As the load the muscle is required to lift decreases, contraction velocity increases. This occurs until the muscle finally reaches its maximum contraction velocity.

In eccentric contractions the muscle actively lengthens. During normal activity, muscles are often active while they are lengthening. Classic examples of this are walking, when the quadriceps (knee extensors) are active just after heel strike while the knee flexes, or setting an object down gently (the arm flexors must be active to control the fall of the object).

As the load on the muscle increases, it finally reaches a point where the external force on the muscle is greater than the force that the muscle can generate. Thus even though the muscle may be fully activated, it is forced to lengthen due to the high external load. This is referred to an eccentric contraction. There are two main features to remark regarding eccentric contractions. First, the absolute tensions achieved are very high relative to muscle's maximum

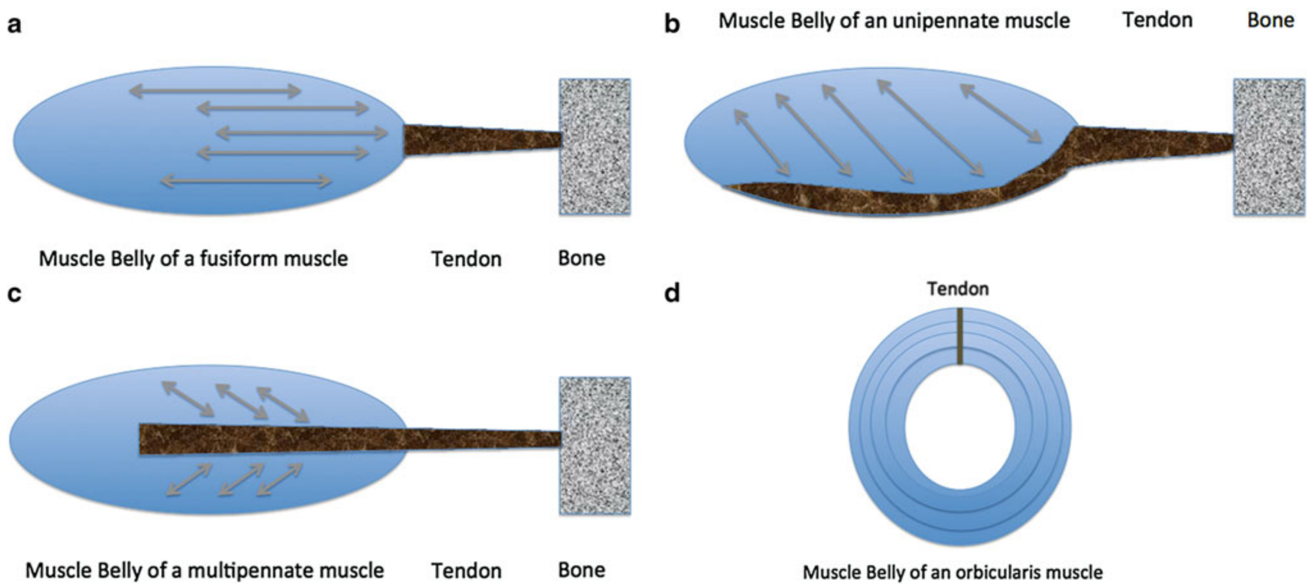

Fig. 2 Schematic drawing of common skeletal muscle anatomy. **a** Fusiform muscle. The fascicles are parallel to the mid-portion of the muscle belly (low strength but high velocity and range of movement). **b** Unipennate muscle. The fascicles insert on one side of the aponeurosis (great strength but low range of shortening). **c** Bipennate muscle. The fascicles insert on two sides of a central aponeurosis (great strength but low range of movement). **d** Orbicularis muscles. These muscles contract concentrically and may not have a real bony insertion but a strong tendinous insertion

tetanic tension generating capacity (you can set down a much heavier object than you can lift). Second, the absolute tension is relatively independent of lengthening velocity. This suggests that skeletal muscles are very resistant to lengthening. The basic mechanics of eccentric contractions are still a source of debate, since the cross-bridge theory, which so nicely describes concentric contractions, is not as successful in describing eccentric contractions. Many muscle injuries and delayed soreness are often associated with eccentric contraction. Moreover, muscle strengthening may be greater using exercises that involve eccentric contractions. It has been recently demonstrated that eccentric contractions that normally determine an injury may stimulate the activation and proliferation of satellite stem cells to guide skeletal muscle regeneration. For this reason therapeutic strategies to combat disuse muscle atrophy may be implemented by the use of eccentric contractions in a rehabilitative setting (Valero et al. 2012). During isometric contraction the muscle is activated, but instead of being allowed to lengthen or shorten, it is held at a constant length. An example of an isometric contraction would be carrying an object in front of you. The weight of the object would be pulling downward, but your hands and arms would be opposing the motion with equal force going upwards. Since your arms are neither raising nor lowering, your biceps will be isometrically contracting. The force generated during an isometric contraction is dependent on the length of the muscle while contracting. Maximal isometric tension is produced at the muscle's optimum length, where the length of the muscle's sarcomeres is on the plateau of the length-tension curve.

Sometimes, a fourth type of muscle "contraction," known as passive stretch, is described. As the name implies, the muscle is being lengthened in a passive state (i.e., not being stimulated to contract) (Fig. 3a–d). An example of this would be the pull one feels in their hamstrings while touching their toes. The usefulness of stretching is still a controversial topic. Several studies investigated optimal stretching techniques causing confusion among researchers and clinicians. Further investigations may be useful to determine how passive and active muscular stretch may improve muscular function as a whole and eventually prevent musculoskeletal derangements (Williams et al. 2013). Examples of muscular contractions on ultrasound (US) examinations are demonstrated in three video clips (VIDEO 1–3) which can be accessed and downloaded via www.extras.springer.com. Representative snapshots of the video clip for isometric contraction are given in Fig. 4.

5 Physiological Notes on Muscular Contraction

From the physiological point of view the musculoskeletal system moves the different segments with respect to each other following the principle of levers. Each muscle is able to provide stability and to produce movement of the levers (bone) around the fulcrum (joint).

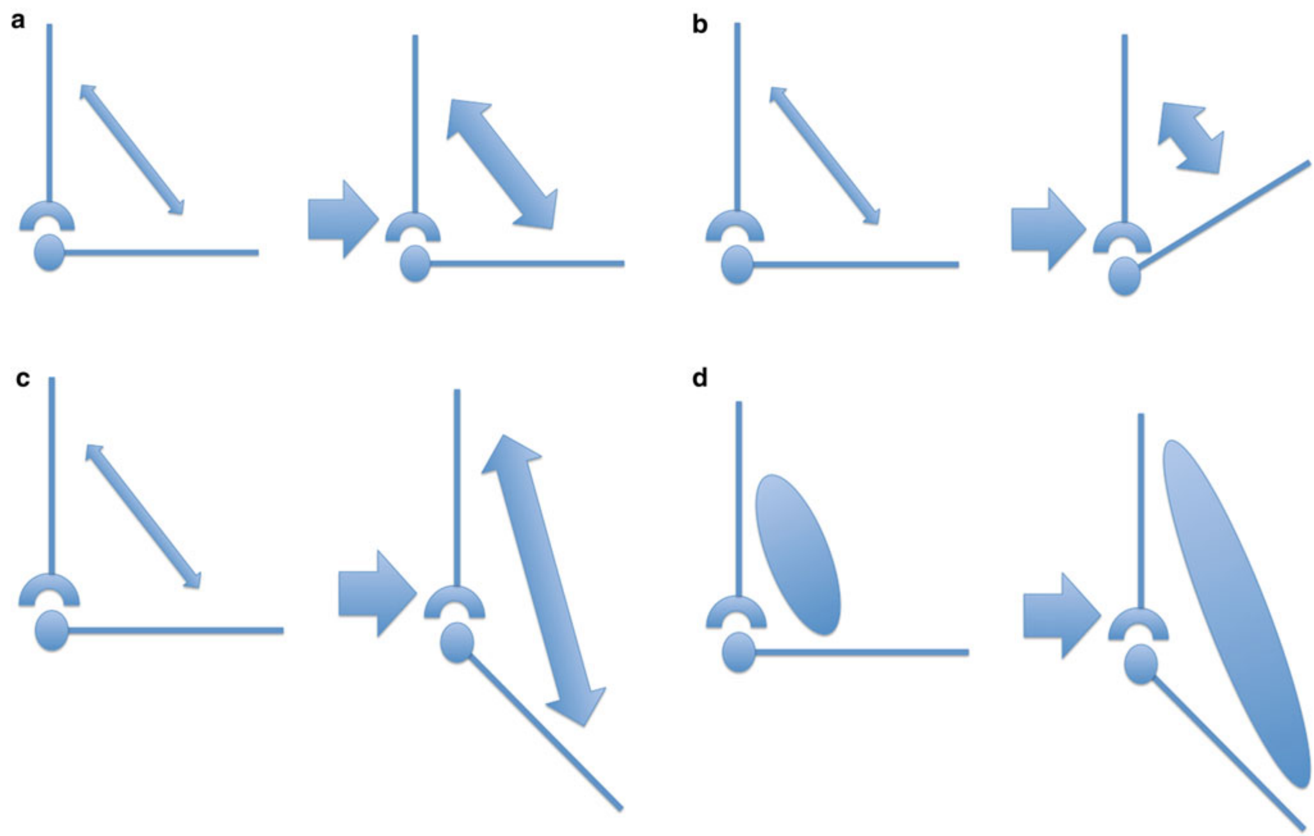

Fig. 3 **a** Isometric contraction. The length of the muscle does not change during contraction. **b** Isotonic contraction. The muscle shortens as it contracts. A typical example of isotonic contraction is the flexion of the arm on the forearm. **c** Eccentric contraction. The muscle lengthens during contraction. **d** Passive stretching. The muscle is lengthened in a passive state without active contraction

The system of levers is divided into three types on the basis of the organization and the distance between the fulcrum to the point of effort and to the load point. We can find all three classes of levers in body muscles.

First Class: The fulcrum lies between the effort and the load. In the human body, a lever of the first class can be found at the level of the head, for example. The weight of the face and of the head may be considered the resistance. The contraction of the posterior neck muscles may be considered the effort to lift the weight. A lever of the first class has a twofold purpose: to increase the speed of movement and to overcome the resistance. In this case the resistance (load) is moved in the opposite direction.

Second Class: The load lies between the fulcrum and the effort. The classical example reported in several textbooks is the principle of the wheelbarrow. A small upward force applied to the handles can overcome a much larger force (weight) acting downwards in the barrow. Similarly, a relatively small muscular effort is required to raise the body weight. In the human body, a lever of the second class can be found in our feet when we stand on our toes and lift our heels off the ground. The resistance (load) is the weight of our body resting on the arch of the foot. The effort is brought about by the contraction of the calf muscle attached to the heel. This leverage allows us to walk. The main purpose of a lever of the second class is to overcome the resistance.

Third Class: The effort lies between the fulcrum and the load. In the human body, a typical example of a lever of the third class is when the biceps contracts, allowing us to lift an object. The elbow may be considered the fulcrum, the object is the resistance (or load), and the biceps muscles contraction is the effort. The load can be moved rapidly over a large distance, while the point of application moves over a relatively short distance. The main purpose of this type of lever is to obtain rapid movement. Human skeletal muscles are shaped also according to their action as levers (Fig. 5a–c).

6 Tendons

Tendons are non-contractile collagenous structures with the function of connecting the muscle to its bony insertion. Tendons are important to transmit forces generated by muscle contraction, to facilitate and to maintain the posture.

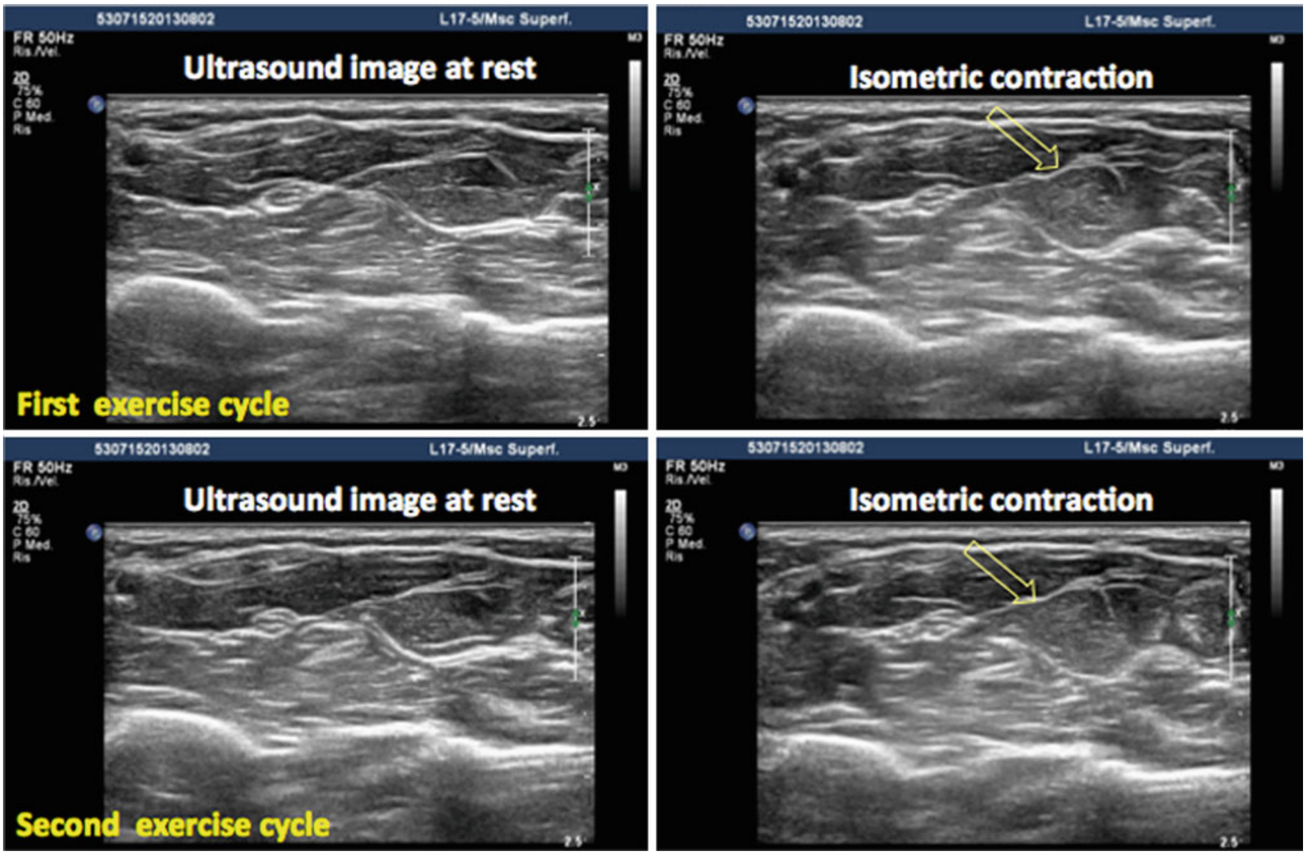

Fig. 4 Examples of different forms of muscular contractions on real-time ultrasound examinations are demonstrated in the three video clips (isometric contraction, isotonic contraction, and passive stretching) which can be accessed and downloaded via www.extras.springer.com. Representative snapshots of the video clips are given for isometric contraction on two subsequent exercise cycles to show the potential of ultrasound to show muscular motion in real-time. The *open arrows* show the time point of contraction

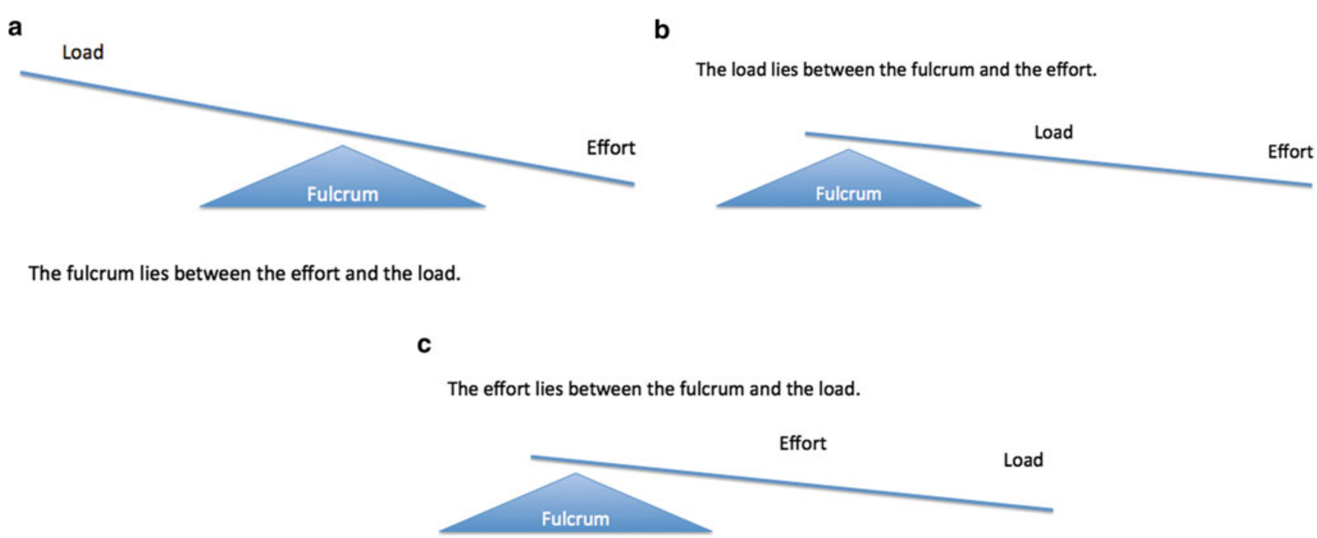

Fig. 5 Principle of levers. **a** First class lever. **b** Second class lever. **c** Third class lever

Several skeletal muscles have both a tendinous insertion and a tendinous origin. Tendons are round or oval in cross-section and are made mainly of type I collagen fibers. These collagen fibers have the task to transmit the force with the minimum area, therefore the fibers are orientated parallel to the long axis of the tendon. Vessels and nerves course within loose connective tissue between the tendon fascicles. Some tendons are surrounded by a synovial sheath, especially when the corresponding muscle has the function to move bony segments for long distances (for example at the level of the fingers). Tendons attach to the periosteum of the bone through fasciculi that continue directly into the cortex of the bone. A plate of fibrocartilage at the site of bony attachment serves to cushion and reinforce the site of attachment. In general, tendons have a variable length according to the muscle of origin. Some tendons may have an intramuscular component or a superficial component resulting in a variable length of the myotendinous junction. Type I collagen fibers of the tendon are accompanied by a few amount of elastic fibers. These elastic fibers are important to increase the resilience and resistance of the tendon. The elastic properties of the tendons allow an elongation up to 6 % during maximum loads preventing damages during movements. Concerning the vascular supply of the tendons it is well known that they have a limited blood supply. This anatomical feature predisposes certain tendons to some typical injuries (e.g., the supraspinatus and the Achilles tendon). Each tendon receives its vascular supply from segmental vessels arising from the surrounding peritendon or, from folds of the mesotendon for those tendons with synovial sheaths (http://www.wheelessonline.com).

7 Aponeuroses

Aponeuroses are connective structures that may be considered flattened tendons. Aponeuroses may be considered separate structures emerging from or within a muscle belly or its surface (for example the tendons of latissimus dorsi and pectoralis major or the aponeurosis of the quadriceps femoris muscle).

8 Muscle–Tendon Junction

The muscle–tendon junction (musculotendinous or myotendinous junction) is the anatomical site where the muscular tissue becomes tendon. This site may be considered a weak area since the majority of traumatic lesions occur at this site. From the microscopical point of view, at this level tendon fibrils insert into deep recesses between finger-like processes of skeletal muscle cells covered by a thick layer of basement membrane. The tendon fibrils attach to the basement membrane of the skeletal muscle cells. Myocytes and tendons fibrils are linked by means of interdigitation to have an increased contact area able to distribute the tensile forces during contraction. The muscle–tendon junction has negligible elastic content and for this reason it has a lower resistance to loads during movement.

9 Imaging

Diagnostic imaging commonly available in clinical practice is able to study the muscles, the tendons, and the bone from a macroscopical point of view in normal and pathological conditions. US, MRI, and CT are widely used with different purposes to visualize the normal anatomy of the musculoskeletal system. Moreover, in recent years, new and technologically advanced imaging techniques have been introduced to study the musculoskeletal anatomy from a physiological and microscopical point of view. For example, elastography has been introduced to assess the elastic properties of tendons and muscles. Using MRI, diffusion tensor imaging (DTI) has been introduced to study the architecture of the skeletal muscle (see also "Correlation of Skeletal Muscle Anatomy to MRI and US Findings" of this book). The DTI technique is based on the measurement of the apparent diffusion of water in a (biological) tissue (Van Donkelaar et al. 1999). It is concluded that DTI fiber directions resemble fascicle directions visible in high-resolution images very well. Moreover, on DTI images it is possible to observe and study specific features of the skeletal muscle such as the pennate insertion on the aponeuroses and the pennation angle. DTI has the potential to be introduced in biomechanical research on skeletal muscle function.

On ultrasound, the evaluation of the skeletal muscle should be made with small-sized probes working in general at high frequencies (frequency band 7–15 MHz). If a large and deep muscle should be evaluated, for example, at the level of the thigh it should be better to use low-frequency probes with high penetration of the US-beam (frequency band 3.5–10 MHz). During the US-machine setting, it is useful to set the focal zone in the appropriate position to improve image quality over the region examined. To depict the normal anatomy of a large wide muscle, such as the rectus femoris and the sartorius, it is possible to use an extended field-of-view. The advantage of US over MRI is that the muscle may be studied "in vivo" in a relaxed status and during contraction. Ultrasound may be used to perform quantitative evaluation of the skeletal muscle. The usefulness of these measurements is reinforced by the observation that muscle size correlates with muscle force (during isometric contractions). Muscular echogenicity may be calculated with US as well as other parameters such as muscle thickness and pennation angle. It has been recently demonstrated that measurement of vastus medialis muscle thickness with US is a reliable, bedside method for monitoring the extent of sarcopenia (Strasser et al 2013). Moreover, it has been demonstrated that US is a highly reproducible method to quantify muscle thicknesses of all muscles both in young people and old sarcopenic individuals. It has been proposed that US muscle thickness measurement, especially of the vastus intermedius muscle and the vastus medialis muscle, could be an accurate and bedside tool for diagnosis and course of sarcopenia in neuromuscular unimpaired patients (Strasser et al. 2013). Muscular hypotrophy or hypertrophy can be easily assessed on short-axis US planes (US probe perpendicular to the main axes of the muscle): during these measurements, care should be taken, however, to avoid any pressure with the probe that can reduce the muscular thickness. It is useful to use the contralateral muscle to increase accuracy. Till date there are many papers suggesting that US can be considered a valuable alternative to MR imaging for cross-sectional area measurements. From the ultrasonographic point of view the echotexture of normal skeletal muscles consists of a relatively hypoechoic background reflecting muscle fascicles and clearly demarcated linear hyperechoic lines related to fibroadipose septa (perimysium). The intramuscular tendons and aponeuroses appear as hyperechoic bands, which are usually better assessed on short-axis images of the muscle. From a histologic point of view, the relative amount of hypoechoic and hyperechoic components of muscle reflects the proportion between connective tissue and muscle fascicles (Fig. 6). This ratio may be variable and depends on the muscle evaluated and it also differs among muscles. On short-axis scans, the muscle echotexture consists of small dot-like reflectors representing fibroadipose septa. As for tendons, muscular fascicles and fibroadipose septa are responsible for muscular anisotropy (Fig. 7). This artifact is clearly visible when a muscle is examined on transverse planes. This artifact depends on the angle between the US beam and the muscle. An angle that deviates from the perpendicular causes the muscle to appear artificially hypoechoic. The arrangement of muscle fibers and fibroadipose septa is important to differentiate semipennate, unipennate, bipennate, or multipennate muscles. On US it is possible to demonstrate intramuscular vessels. Depiction of intramuscular vessels is important in several clinical situations. For example, color Doppler US resulted accurate for the pre-surgical assessment of deep inferior epigastric perforator procedure for breast reconstruction and US was able to assess the intramuscular course of the perforator vessel and in identifying superficial venous communications (Cina et al. 2010). Moreover, color Doppler US was superior for measuring perforator artery calibers, and CT angiography was superior for estimating the intramuscular course of the perforator vessel and for identifying superficial venous communications (Cina et al. 2010). US has the big advantage to reduce the role of CT and thus the exposure of patients with radiation only to selected cases (Cina et al. 2010). On US the outer muscle fascia (epimysium) normally appears as a well-delineated echogenic envelope circumscribing the hypoechoic muscular tissue. In complex muscles, an individual hyperechoic fascial sheath surrounds each muscle belly, thus helping the examiner to recognize the different heads. Sometimes, it is possible to demonstrate focal interruptions of the muscle fascia found at the points where nerves, veins, and arteries (perforating vessels) enter the muscles.

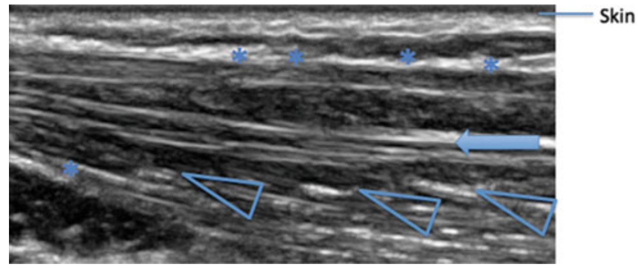

Fig. 6 Skeletal muscle anatomy. Individual muscle fibers are arranged in fascicles. Loose connective tissue strands envelope the fibers (endomysium), the fascicles (perimysium), and the whole muscle (epimysium). On the long-axis 17-5 MHz US image of flexor tendons of the forearm there are multiple hyperechoic lines (*arrowheads*) consistent with perimysium. Some lines converge to form the aponeurosis (*arrow*). The epimysium (*asterisks*) demarcates the outer boundaries of the muscle

Conventional MRI uses gyration of protons (^{1}H) basically of water and carbohydrate compounds for image acquisition. At ^{1}H MRI muscular tissue has a different appearance according to the specific sequences adopted. In general the muscle is isointense on T1-weighted sequences, whereas tendons and aponeuroses are hypointense on both T1-weighted and T2-weighted sequences due to the low water content and high collagen content (Fig. 8). Fat has a shorter T1 relaxation time relative to muscle and pure water, so that fat appears bright on T1-weighted images and thus the T1-weighted sequence is best for imaging fatty replacement of muscle seen in chronic disease. On T2-weighted images muscle and tendons have a short T2 relaxation time, while water and therefore also edematous or inflamed tissues have a long relaxation time and T2-weighted sequences, especially with additional fat suppression techniques, which are better for detecting acute or inflammatory changes of muscle that may be related to edema or increased blood flow. Also, the MRI signal on T1- and T2-weighted images is susceptible to blood degradation products and, of note, the appearance of muscular hematomas on MRI is primarily dependent on the age of the hematoma and on the imaging sequence or parameters (Fig. 9). Therefore, muscle trauma sequelae like muscular hematomas after blunt trauma can nicely be verified and monitored using MRI. Detailed descriptions of muscular MRI techniques (see "Whole-Body MRI for Evaluation of the Entire Muscular System", "Skeletal Muscle MR Imaging Beyond Protons: With a Focus on Sodium MRI in Musculoskeletal Applications", "MR Spectroscopy and Spectroscopic Imaging for Evaluation of Skeletal Muscle Metabolism: Basics and Applications in Metabolic Diseases") and MRI applications (see "MRI of Muscle

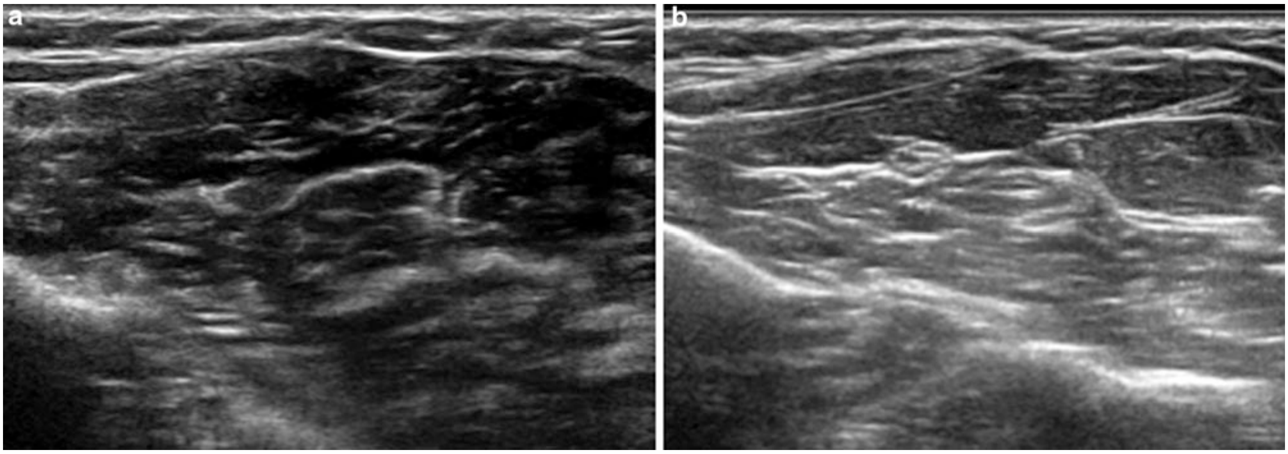

Fig. 7 Muscle anisotropy. Short-axis 17–5 MHz US images of the flexor muscles of the forearm examined with an almost perpendicular angle (**a**) between the transducer and the muscle fibers and an oblique angle (**b**). In (**b**), the muscle appears diffusely hyperechoic owing to the highest specular reflectivity from the perimysium interfaces. Artificial hypoechoic patterns should be differentiated from mild strains

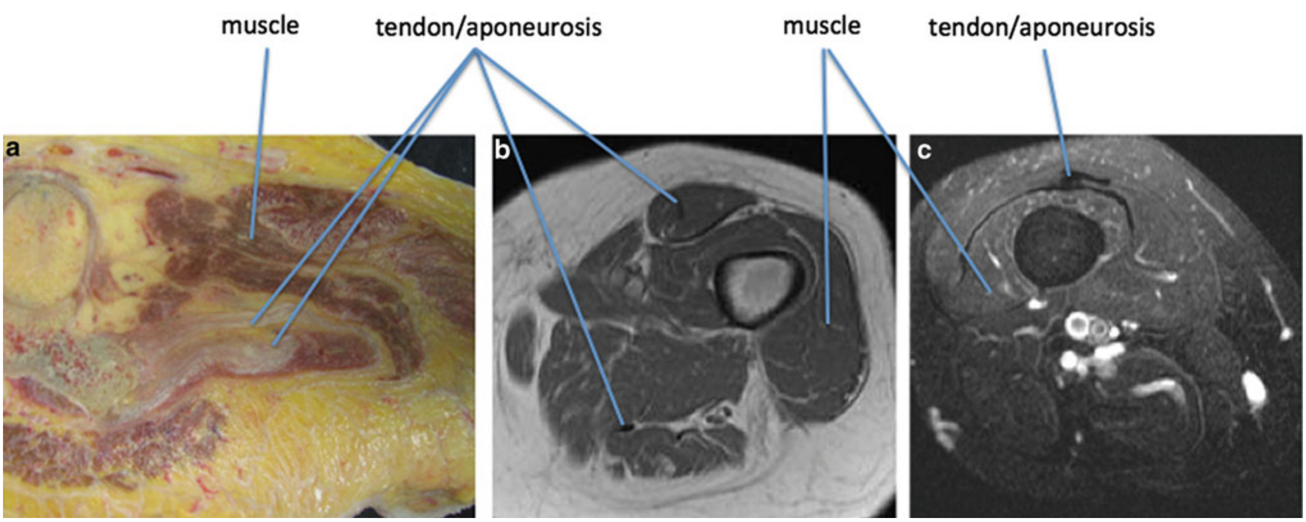

Fig. 8 Gross anatomy (**a**), transverse T1-weighted fast spin-echo (**b**) and T2-weighted fast spin echo (**c**) with fat saturation of the human thigh showing the appearance of muscle, tendons, and aponeuroses

Injuries", "MRI in Muscle Dystrophies and Primary Myopathies", "MRI in Inflammatory Myopathies and Autoimmune-Mediated Myositis", "MRI in Muscle Channelopathies", "MRI in Muscle Tumors and Tumors of Fasciae and Tendon Sheaths") are reported in the second and third parts of this book.

10 Anatomical Variants

Muscular anatomical variants are more common than normally thought. Muscular anatomical variants include not only supernumerary or accessory muscles, but also absence, deviation from a normal course, and an anomalous origin or insertion (Sookur et al. 2008).

Among these variants, the absences of a muscle, a supernumerary muscle, or a deviation from the normal course (anomalous origin or insertion) are the most frequent abnormalities amenable of diagnostic imaging evaluation. Accessory muscles are distinct muscles that are generally not present in the population and may be encountered in adjunct to the normal muscles generally described in anatomical textbooks.

The first report dealing with accessory muscles was based on cadaveric dissection or on surgical reports. With the increased use of medical imaging, both US and MRI are

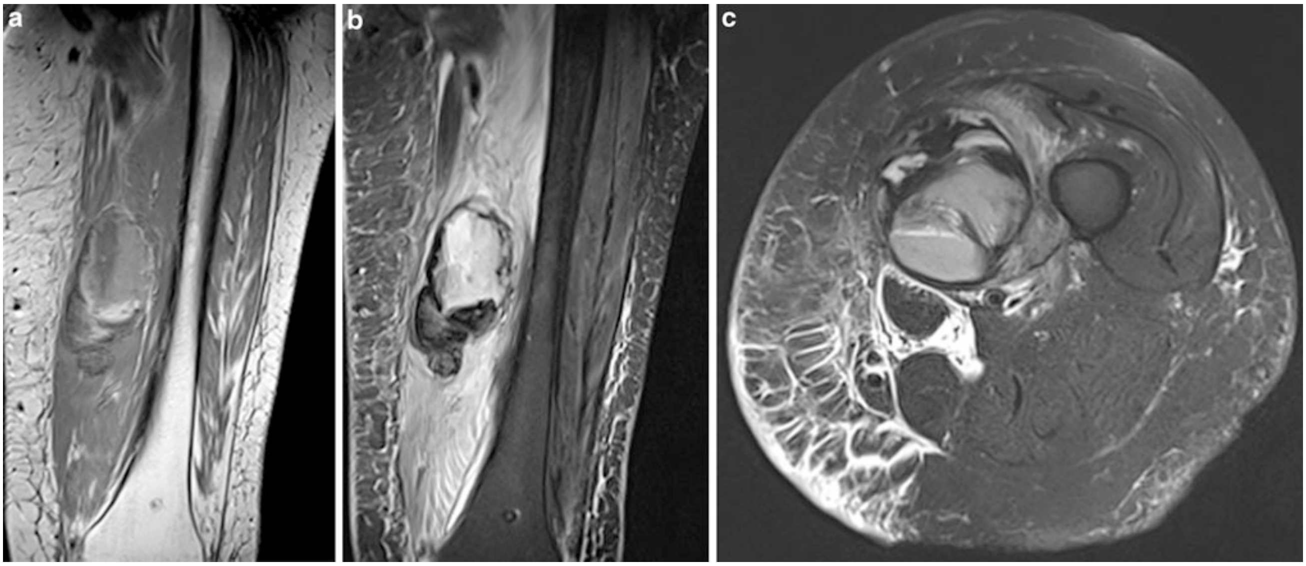

Fig. 9 78-year old-woman under anticoagulatory therapy with phenprocoumon and presentation with sudden swelling and pain of left thigh. Coronal STIR sequence (**a**), coronal T1-weighted (**b**), and axial fat-suppressed T2-weighted 3 Tesla MR images of the left thigh demonstrate large, subacute, muscular hematoma of the vastus medialis muscle (images courtesy of Prof. Dr. M.-A. Weber, Heidelberg)

Table 1 Accessory muscles or anatomical variants amenable of imaging evaluation at the level of the six major joints

	First choice	Second choice	Accessory muscles or variants to be detected	Notes
Shoulder	MRI	US/CT	Additional heads of the biceps brachii (three- or four-headed variant)	MRI is the first choice due to its panoramic characteristics. CT has low contrast resolution
			Axillopectoral muscle	
			Chondroepitrochlearis (Chondrohumeralis)	
Elbow	US	MRI	Anconeus epitrochlearis	The anconeus epitrochlearis may be associated with cubital tunnel syndrome
			Accessory brachialis	
Wrist and Hand	US	MRI	Accessory abductor digiti minimi	US is usually used as first choice technique
			Anomalous flexor digitorum superficialis of the index finger	
			Palmaris profundus	
			Extensor digitorum brevis manus	
Knee	MRI	US	Accessory slips of the medial and lateral gastrocnemius muscle	MRI may be better due to the deep location of the structures to be evaluated
Foot/ Ankle	US	MRI	Accessory peroneal muscles (lateral)	US is generally used as first choice technique
			Flexor digitorum accessorius longus (medial)	
			Peroneocalcaneus internus	
			Accessory soleus	
			Tibiocalcaneus internus	

able to detect anatomical variants related to the accessory musculature, thus helping to differentiate normal variants from pathological findings such as a soft tissue mass. From the clinical point of view, accessory muscles are often asymptomatic and non-visible at clinical examination. However, they may be responsible for clinical symptoms in case of hypertrophy or associated lesions. The mass effect produced by the additional muscle belly, possibly mimicking a soft tissue tumor, a compression or displacement of adjacent structures, such as nerves, vessels, and tendons near osteofibrous tunnels and exercise-related pain as a probable result of localized compartment syndrome or inadequate blood supply received by the muscle are the three main causes of complaints among patients having accessory muscles (Martinoli et al. 2010).

Accessory muscles and anatomical variants are commonly overlooked at imaging evaluation, but the appropriate use of US and MRI may be useful to detect these abnormalities.

In Table 1 is reported the most frequent anatomical variants amenable for imaging evaluation and for each of them is reported the best imaging technique that should be used for detection and appropriate diagnosis.

At the level of the shoulder the axillopectoral muscle crosses the axilla as a triangle arising from the external border of the latissimus dorsi; the chondroepitrochlearis or chondrohumeralis muscle is an extremely rare muscle variant that arises from either the ventral edge of the pectoralis major muscle, the osteochondral junction of the fifth and sixth costal cartilages, or the aponeurosis of the external oblique muscle and inserts into the medial intermuscular septum or the medial epicondyle (Figs. 10 and 11) after crossing the axilla and the upper arm (Martinoli et al. 2010). Additional heads of the biceps brachii resulting in a three- or four-headed variant are extremely rare, and the data are limited to case reports. In a case report reporting a four-headed biceps (Vazquez et al. 2003), the first supernumerary was located between the lesser tuberosity and the coracobrachialis and brachialis muscles and joined the long head of the biceps at the level where the short head joined. The second supernumerary head originated from the humerus at the site of insertion of the coracobrachialis and joined the biceps tendon at the bicipital aponeurosis in the distal third of the arm.

At the level of the elbow the most commonly encountered accessory muscle is the anconeus epitrochlearis (Fig. 12). The anconeus epitrochlearis or accessory anconeus is a small accessory muscle of the posteromedial aspect of the elbow that extends from the medial epicondyle to the olecranon with an almost transverse course. Sometimes the anconeus epitrochlearis may substitute the cubital tunnel retinaculum (Osborne ligament).

At the wrist and hand there are four most relevant accessory muscles: the accessory abductor digiti minimi, the anomalous flexor digitorum superficialis of the index finger, the palmaris profundus, and the extensor digitorum brevis manus. These muscles are in close relationship with non-muscular structures belonging to osteofibrous tunnels. These muscles may cause symptoms of ulnar neuropathy (Guyon tunnel syndrome), or median neuropathy (carpal tunnel syndrome). The extensor digitorum brevis manus and the anomalous flexor digitorum superficialis of the index finger may mimic a palpable soft tissue mass (Martinoli et al. 2010).

At the knee, variations of the origin of the medial and lateral heads of the gastrocnemius consist of anomalous origins and accessory slips. The medial head of the

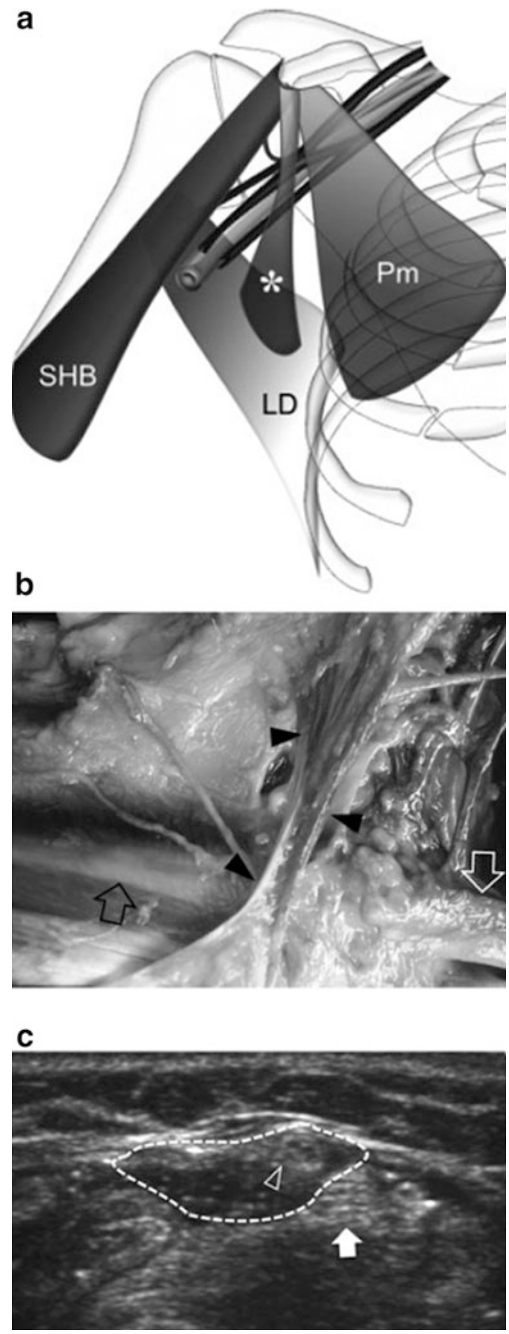

Fig. 10 Axillary arch muscle. **a** Schematic drawing of the axilla illustrates an axillary arch muscle (*asterisk*) originating from the latissimus dorsi (LD) and inserting into the coracoid after bridging the axillary artery and the nerve cords of the brachial plexus. The short head of the biceps (SHB) and the pectoralis minor muscle (Pm) also arise from the coracoid. **b** Cadaveric image of the axilla shows the axillary arch muscle (*arrowheads*) as a slender myotendinous band crossing over the nerve cords and the axillary artery (*arrows*). **c** Transverse 10–5 MHz ultrasound image shows the axillary muscle (*dashed line*) in its cross section, adjacent to the median nerve (*arrow*). Note the intramuscular tendon (*void arrowhead*) of the accessory muscle. Printed with permission of Thieme from Martinoli et al. (2010)

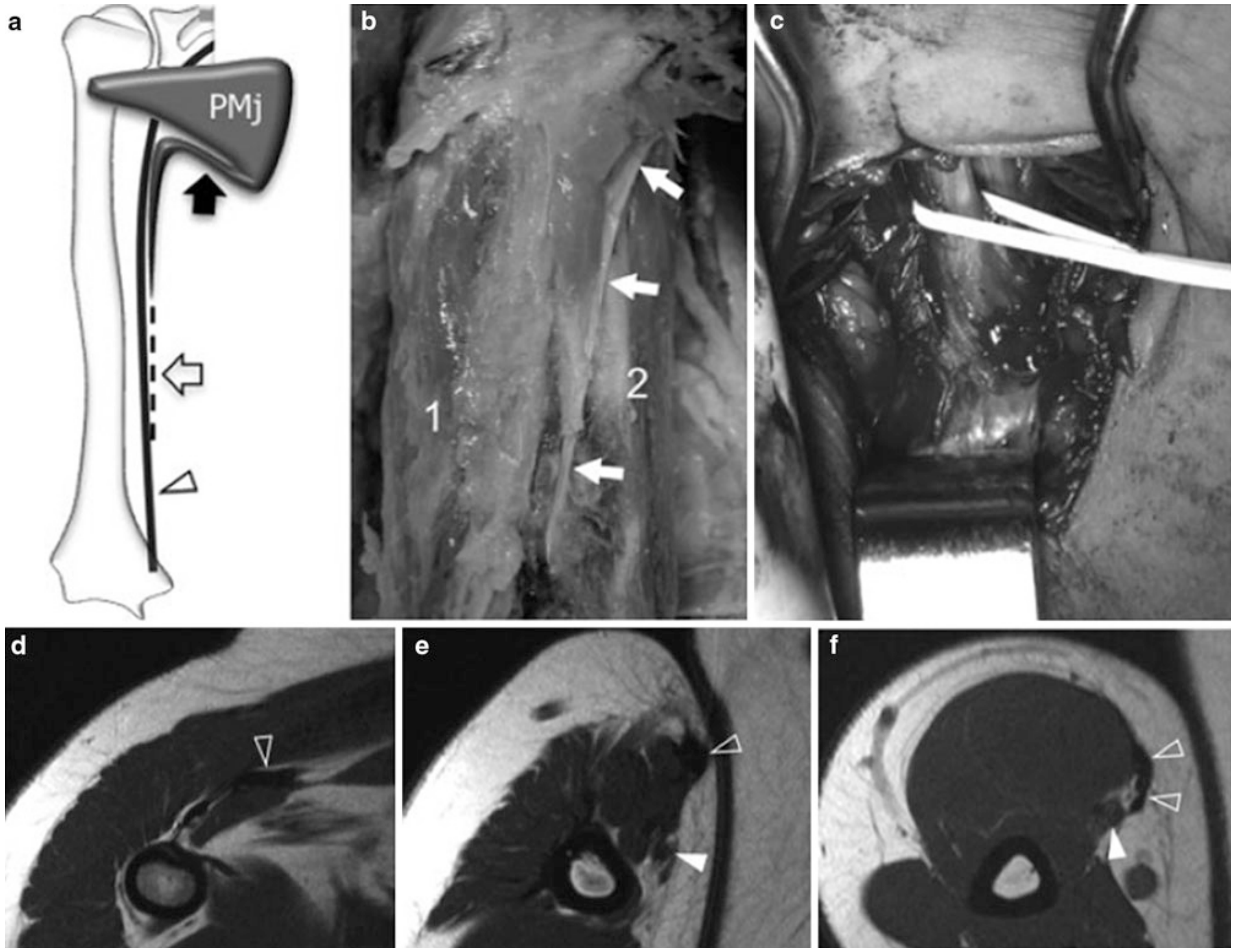

Fig. 11 Chondroepitrochlearis muscle. **a** Schematic drawing with **b** cadaveric and **c** surgical correlation illustrates the chondroepitrochlearis muscle (*black arrow*) arising from the lowest fibers of the pectoralis major (PMj) and descending the medial aspect of the arm with a slender tendon (*white arrow*), between the biceps (1) and the triceps (2). The chondroepitrochlearis tendon travels alongside the medial neurovascular bundle (*arrowhead*) of the arm. **d–f** Axial T1-weighted magnetic resonance imaging of the upper arm obtained from (**d**) cranial to (**f**) caudal demonstrate a hypointense cord (*void arrowheads*) descending the arm in close relationship with the neurovascular bundle (*white arrowheads*) reflecting the long tendon of a chondroepitrochlearis muscle. Printed with permission of Thieme from Martinoli et al. (2010)

gastrocnemius may have an aberrant origin, arising from the region of the intercondylar notch rather than the medial femoral condyle. The lateral head of the gastrocnemius may have an aberrant origin, arising more medially from the posterior femur but maintaining its position lateral to the popliteal artery. An accessory slip of the medial head of the gastrocnemius may arise from the intercondylar notch, passing between the popliteal artery and vein and inserting into the medial head of the muscle. An accessory slip of the lateral head of the gastrocnemius has also been described originating from the posterior cortex of the distal femur, medial to the lateral head. The slip courses anterolateral to the popliteal vessels, inserting into the lateral head of the gastrocnemius. From the clinical point of view, an anomalous relationship between the popliteal artery and the proximal gastrocnemius may be responsible to manifest clinically with popliteal artery entrapment syndrome (Sookur et al. 2008).

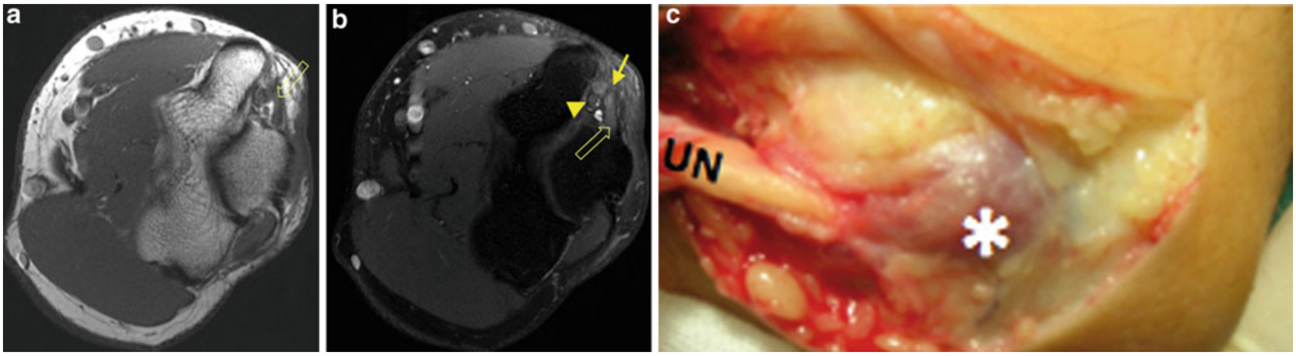

Fig. 12 38-year-old man with anconeus epitrochlearis muscle that has led to a cubital tunnel syndrome. The T1-weighted 3 Tesla MR images **a** show the accessory anconeus epitrochlearis muscle next to the cubital tunnel (*open arrows*). To cure the irritation of the ulnar nerve, the muscle has been split surgically (*closed arrow*). The fat-saturated contrast-enhanced T1-weighted MR image **b** demonstrates that the nerve exhibits no pathologic enhancement (arrowhead) and that the accessory muscle shows postoperative subtle enhancement. Furthermore, the intraneural T2 signal of the ulnar nerve was normal (image not shown). The anconeus epitrochlearis or accessory anconeus muscle is thought to represent an atavistic muscle that is usually found as a remnant in form of the epitrochleoanconeus ligament. It can be found intact in ∼5 to ∼35 % of cadavers **c** and in a recent MRI study this accessory muscle has been reported in about 25 % of patients (Husarik et al. 2009) (images courtesy of Dr. J. Kollmer, Heidelberg) *UN* ulnar nerve, *asterisk* anconeus epitrochlearis muscle. Part Figure c is printed with permission of Springer from Tagliafico et al. A Radiologically Guided Approach to Musculoskeletal Anatomy

Accessory muscles are fairly common about the ankle. They include the accessory peroneals (peroneus quartus and peroneus tertius), the accessory flexors (flexor digitorum accessorius longus, peroneocalcaneus internus), and the accessory soleus.

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