# Physiology of the Masticatory System

3

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**Abstract**

This chapter is a review of the physiology of the masticatory system from both a peripheral and central perspective. From the peripheral perspective, important components include the muscles that drive movements and the associated somatosensory and motor nerves. The basic functional unit of muscle is the motor unit. Most mandibular muscles have a complex internal architecture, and selective activation of regions within the muscles is thought to contribute to the complex array of finely controlled forces and movements that are characteristic of orofacial function. From the central perspective, the extensive array of orofacial somatosensory receptors encodes peripheral information (about, e.g., tooth contacts, food bolus consistency, mandibular position and movement) that is transmitted to higher centers of the brain to allow us to sense our environment and also to provide continual feedback to refine orofacial movements. The face primary motor cortex plays a key role in the generation of voluntary orofacial movements, and the masticatory central pattern generator is important in the generation of masticatory (i.e., chewing) movements. The orofacial sensorimotor regions of the brain are in receipt of extensive orofacial somatosensory inputs and are capable of considerable adaptability (through neuroplastic changes) in response to changes to the peripheral motor apparatus (e.g., dentures, implants). The peripheral and central nociceptive pathways can become sensitized and responsive even to non-noxious (non-painful) stimuli. These effects can contribute to the allodynia and hyperalgesia seen in acute and chronic pain states. Older models of the effects of pain on motor activity are being superseded by more complex models that emphasize a complex reorganization of muscle activity in the presence of pain as well as emphasizing a role for psychological aspects.

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## 3.1 Physiology of the Masticatory System: Peripheral Aspects

### 3.1.1 The Muscles

The muscles involved in mastication are the masticatory, facial, and tongue muscles. Swallowing involves these muscles and also other muscles such as those controlling the palate, pharynx, and esophagus. The masticatory, facial, and tongue muscles are driven by α-motoneurons located within, respectively, the trigeminal, facial, and hypoglossal motor nuclei within the brainstem; many motoneurons involved in swallowing are located in the nucleus ambiguus, also within the brainstem. The functional anatomy of the masticatory muscles as well as the morphology and physiology of masticatory muscles and motor units have been described in detail in previous reviews (Hannam and McMillan 1994; Korfage et al. 2005a, b; Miller 1991; van Eijden and Turkawski 2001). The following summarizes some of the main features and will concentrate on the masticatory muscles, with reference to the facial and tongue muscles as needed.

The masticatory muscles are capable of generating high forces necessary for breaking down tough foods in chewing but also are capable of generating low forces with precision as required, for example, in the precise positioning of the upper and lower anterior tooth incisal edges as required in clearly articulated speech sounds such as the "s" sound. How do the muscles work to achieve this remarkable flexibility? In this first section, the anatomy and physiology of the masticatory muscles will be described, and aspects of the complex central neural control will be described in the next section.

#### 3.1.1.1 The Motor Unit

Muscles exert force by contracting or shortening. The smallest contractile element of a muscle is termed the motor unit. A motor unit consists of an α-motoneuron plus all the muscle fibers innervated by (i.e., connected to and activated by) that α-motoneuron. The trigeminal motor nucleus in the brainstem contains the cell bodies of masticatory muscle α-motoneurons (see below). Each cell body gives rise to an efferent axon that travels out in motor nerves to then branch and terminate at special synapses called neuromuscular junctions on all the muscle fibers of that motor unit (Fig. 3.1). Action potentials travelling along each α-motoneuron axon pass to all the muscle fibers of that motor unit to cause them all to contract in unison (Fig. 3.1b). As the action potentials arrive at the presynaptic terminal, calcium ions enter the neuronal terminal and cause vesicles containing acetylcholine (a neurotransmitter) to fuse with the presynaptic membrane and release acetylcholine. The acetylcholine then binds to nicotinic acetylcholine receptors on the muscle membrane (the sarcolemma) which allow ionic flow (sodium ions) into the muscle fiber. This ionic flow results in the generation of action potentials which travel the length of the muscle fiber; the action potentials enter the muscle fibers via a system of T-tubules, and this is followed by a sudden release of calcium ions from the sarcoplasmic reticulum. The calcium ions, together with ATP, result in successive cycling of actin and myosin filaments within the sarcomeres, which are the contractile elements of a muscle fiber. Each sarcomere contains overlapping myosin and actin filaments that are the basic structural elements that work to pull the z bands on either side of the sarcomere closer to each other in a muscle contraction. Many sarcomeres are in series in any one muscle fiber so that they can generate adequate force and length change during contraction, and with functional changes the sarcomere numbers can change to reestablish optimal overlap of filaments (Goldspink 1998). The masticatory muscles contain "superfast myosin," not generally seen in limb or trunk muscles, and which has very high ATPase activity which allows the masticatory muscles to contract very quickly and very forcefully.

#### 3.1.1.2 There Are a Range of Sizes of Motor Units

The size of a motor unit is defined in terms of its innervation ratio which is the number of muscle fibers innervated by the α-motoneuron of the motor unit. Small motor units consist of only a few muscle fibers, for example, motor units in the

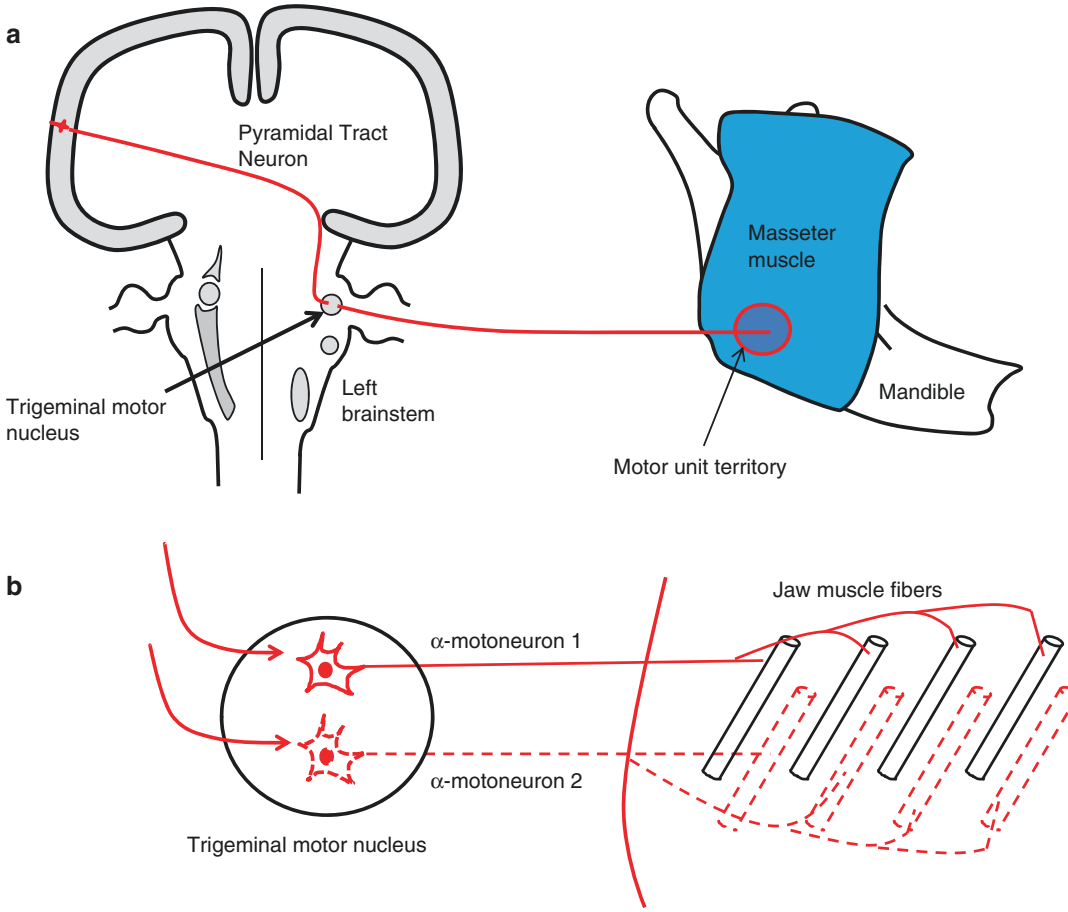


**Fig. 3.1** The upper panel (**a**) shows a diagrammatic brain (hemispheres not to scale) with a pyramidal tract neuron passing to an α-motoneuron in the trigeminal motor nucleus in the brainstem. This α-motoneuron passes to innervate (i.e., drive) a motor unit in the masseter muscle. The lower panel (**b**) is a higher detail of the trigeminal motor nucleus with 2 α-motoneurons sending axons to innervate two groups of four muscle fibers within the masseter muscle. The combination of α-motoneuron one plus the four muscle fibers in black constitutes one motor unit; α-motoneuron two plus the four muscle fibers in *dotted red outlines* constitutes another motor unit. Therefore two motor units are shown. The muscle fibers of one motor unit are interleaved with muscle fibers of the other motor unit. Only four muscle fibers are shown, but for the masticatory muscles, there can be many hundreds of muscle fibers activated when one motor unit becomes activated

extraocular muscles controlling the eyeball may contain only 5–10 muscle fibers for each α-motoneuron in each motor unit. When these motor units are activated, they generate only low forces as required for fine positioning of the eyeball for small and precise eye movements. The lower limb muscles (e.g., the quadriceps femoris muscle), on the other hand, have high innervation ratios of, for example, >1000 muscle fibers for each α-motoneuron of a motor unit, and therefore when one motor unit activates, much larger forces are generated as required for the much larger forces that lower limb muscles need to generate in supporting the weight of the body. Masticatory muscles have intermediate innervation ratios of ~500–1000 muscle fibers per motor unit.

The muscle fibers of a motor unit are contained within the motor unit territory, and there are multiple territories within a muscle (Fig. 3.1a). As indicated in Fig. 3.1b, the muscle fibers of one motor unit are intermingled with the muscle fibers of other motor units. This intermingling of muscle fibers of one motor unit with fibers of other motor units may help to smooth out the twitch forces

(see below) generated by motor units. Typical motor unit territories for the masseter muscle have been mapped at covering a distance of ~5 mm anterior-posteriorly and mediolaterally. Therefore when a motor unit contracts, it exerts force only over a small part of the muscle. So when motor units are activated, the magnitude and direction of the force generated depend on the location of the motor unit within the muscle.

#### 3.1.1.3 Types of Motor Units

There is added complexity in that there are three general types of motor units that have been classified on the basis of histochemical and physiological properties. Histochemically, they are classified on the basis of histological staining features, as Type I, Type IIA, and Type IIB motor units, and these equate with the physiological classification that divides motor units into Type S (slow), Type FR (fast, fatigue resistant), and Type FF (fast, fatiguable) motor units, respectively. The three types contribute to variations in the magnitude of force that different motor units can generate. The Type S (or Type I) motor units (Fig. 3.2a) contain fewer muscle fibers within each motor unit, and they are slow and produce low forces (~2 g weight, Fig. 3.2c), but since they have high levels of myoglobin and mitochondria and a rich capillary bed (and are therefore termed red muscle fibers), they are fatigue resistant. Fatigue resistance means that these motor units will generate the same force repeatedly every time they are activated, and they can do this for sustained periods (hours). These motor units are therefore good for the generation of low forces for a long time as required for postural support as, for example, in keeping us sitting upright or keeping our mandible in the postural rest position. At the other end of the spectrum are the Type FF (Type IIB) motor units (Fig. 3.2b) which are fast contracting and produce the highest forces (~10 g weight, Fig. 3.2c). They, however, fatigue rapidly, that is, these motor units cannot generate the same force repeatedly every time they are activated, and over even a few seconds of repeated activation, the force they are able to generate rapidly decreases. When we clench as hard as we can or sprint down an athletic track, we can generate high forces, but we can only maintain these maximum forces for a few seconds. This is because the Type FF motor units that are generating most of the forces required for these high-force activities are very quickly fatiguing. The Type FR (Type IIA) motor unit (not shown in Fig. 3.2) is an intermediate type of motor unit and as such generates forces that are intermediate between the forces generated by the Type S and Type FF motor units. The fatigue resistance of these motor units is also considered intermediate. They are not capable of generating forces close to their maximum force for as long a duration as can be accomplished by the repeated activations of the Type S motor units; however, the Type FR motor units can generate forces close to their maximum force for a longer duration than for the Type FF motor units. Within each masticatory muscle, there is regional variation of fiber type, and this can differ between subjects (Korfage et al. 2005a, b) likely because of differing functional demands (van Eijden and Turkawski 2001). Furthermore, muscle fiber type may change over time in response to a number of variables including altered mandibular function, jaw stretch, and aging (Korfage et al. 2005a).

A fundamental principle is that motor units are activated (or recruited) in order of size. This size principle of motor unit recruitment was proposed by Elwood Henneman in the 1950s. It means that the smallest motor units of a muscle, the Type S motor units, are recruited first in a muscle contraction, and then with larger forces, larger motor units of the Type S class are recruited followed by the Type FR and Type FF motor units. Therefore, it is only at the higher forces in a contraction that the Type FF motor units become activated. It is important to note that in the masticatory muscles, some motor units are heterogeneous and contain different fiber types (van Eijden and Turkawski 2001).

There is good evidence now that the centers of the brain that activate muscles are able to selectively activate specific regions or subcompartments within the masticatory muscles independently of other regions. This ability of subcompartments of the masticatory muscles to be selectively activated independently of other regions is called functional heterogeneity

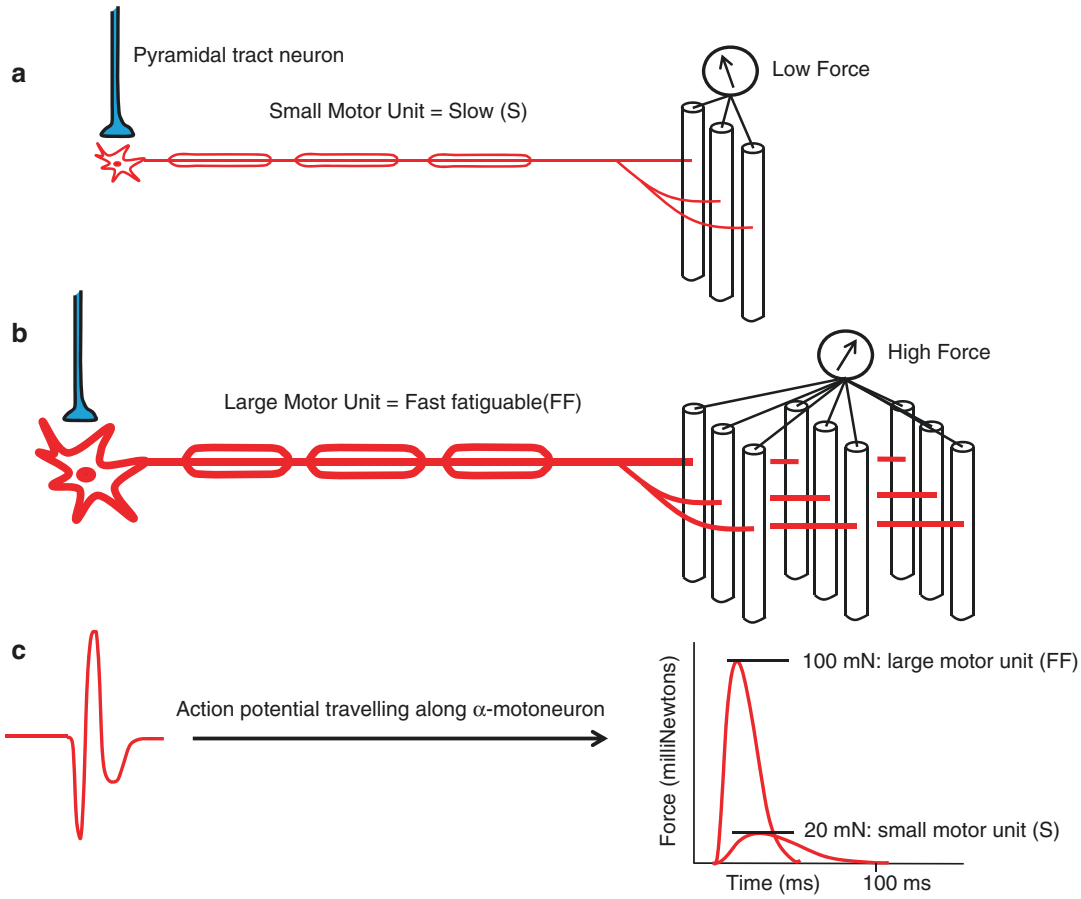


**Fig. 3.2** Panel (**a**) shows a small Type S (slow) motor unit where the α-motoneuron innervates only a few muscle fibers (3 shown here). When this Type S motor unit activates, it generates low forces, but because it is fatigue resistant, the motor unit can keep generating the same forces for a long time. Panel (**c**) shows an action potential travelling along the α-motoneuron of this small, slow motor unit to cause a single brief contraction of the muscle fibers of this motor unit, the so-called twitch contraction. The force generated by a single twitch contraction of this slow motor unit is about 20 mN (~2 g of force) as shown in the graph on the right. Panel (**b**) shows a large Type FF (fast, fatiguable) motor unit where the α-motoneuron innervates many muscle fibers (can be many hundreds). When it contracts, it generates large forces, but because it rapidly fatigues, the motor unit can only keep generating the same forces for a few seconds before the force being generated from this motor unit rapidly decreases. An example of the large force generated by this Type FF motor unit is shown in panel (**c**) where a force of about 100 mN (~10 g of force) is shown in the graph on the right

(Blanksma and van Eijden 1990, 1995; Phanachet et al. 2001, 2003; Weijs and Kwa 1995). The concept contrasts with anatomical views that a muscle contraction involves increasing levels of evenly distributed activity throughout a muscle. Rather, it appears that in many muscles of the body and probably all of the masticatory muscles, the brain can selectively activate those regions of a muscle that are biomechanically best suited to contribute forces in the required direction (i.e., generate a required force vector) to allow a particular movement or force to be generated. The next section explains how many of the masticatory muscles are organized to allow this selective activation.

#### 3.1.1.4 Muscles Have a Complex Internal Architecture

Further complexity arises by the fact that most of the masticatory muscles have a complex internal architecture, that is, a complex arrangement of

the muscle fibers. This means that instead of muscle fibers travelling the full length of the muscle from origin to insertion, many, but not all, of the masticatory muscles consist of groupings of short muscle fibers that are arranged in a pennate or feather-like manner.

Figure 3.3 illustrates this pennate arrangement for the masseter muscle. The muscle fibers of the masseter are not long muscle fibers that extend from the zygomatic arch (the origin) all the way to the ramus of the mandible (the insertion). Rather, the masseter consists of collections of short muscle fibers (red bands in insert B on the right of Fig. 3.3) that are surrounded by aponeurotic, fascial, or tendon sheaths (black bands in Fig. 3.3a, b). This arrangement of muscle fibers resembles a feather, hence the name, pennate. Forces are produced that are at an angle (the pennation angle) to the long axis of the muscle when motor units on one side of an aponeurosis contract. Therefore, a force vector is generated by these muscle fibers that will be at an angle to the force vector that would be generated if the muscle fibers passed directly from the zygomatic arch to the ramus without pennation. This pennate arrangement of muscle fibers appears to allow for a much greater range of force directions that can be imposed on the mandible when different parts of the masseter muscle contract than the narrow range of closing directions of force that would be applied to the mandible if the muscle fibers were arranged in a unidirectional manner and ran from the zygomatic arch to the ramus.

The medial pterygoid and temporalis muscles also have similar complex internal architectures, while the lateral pterygoid and digastric muscles

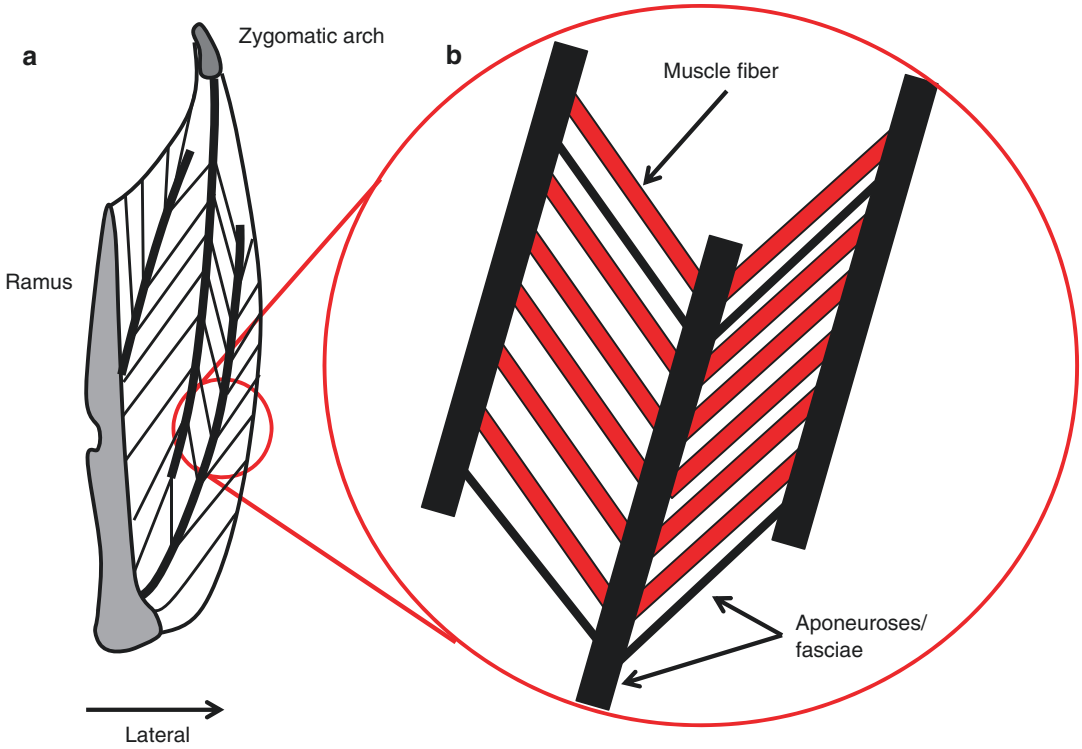


**Fig. 3.3** Panel (**a**) shows a coronal section through the left masseter muscle (looking from the front). The *black bands* (3 are shown) represent aponeurotic sheaths that pass from the zygomatic arch or the ramus of the mandible into the muscle. These aponeurotic sheaths are connected by smaller sheaths or fasciae (**b**). Muscle fibers do not run from the zygomatic arch down to the ramus of the mandible but rather run from one aponeurotic sheath to another. So when muscle fibers of a motor unit on one side of an aponeurosis contract, they exert forces at a markedly different angle to those on the other side of the same aponeurosis. A wide range of force vectors (different magnitudes and directions of force) are therefore possible depending on how the brain activates the range of motor units available within the masseter muscle. A similar complexity of force directions appears to occur also in the medial and lateral pterygoid muscles and the temporalis muscles

appear to have simpler internal muscle fiber arrangements with many of the muscle fibers passing the full length of the muscle. Nonetheless, these complexities of muscle fiber architecture within most of the masticatory muscles provide the possibility for a wide range of directions with which forces can be applied to the mandible. Selective activation of these regions, or subcompartments, provides a range of forces and movements enabling a wide range of mandibular tasks.

The above description points to a considerable flexibility in the activation of motor units within muscles. Higher centers of the brain appear capable of activating those motor units in whatever muscles that are most ideally placed for the task at hand. Therefore, in the production of mandibular, facial, or tongue movement, the higher brain centers (i.e., sensorimotor cortical regions; see below) that drive voluntary movements are not organized in terms of muscles but rather the elemental components of muscles, namely, the motor units. Rather than sending command signals to activate muscles in sequence or simultaneously, the higher centers of the brain only "think" in terms of activating those motor units, wherever they may be located, that are biomechanically best suited to generate the force vector required for that particular mandibular movement. Thus, for example, a grinding movement of the mandible to the left side from intercuspal position and with the teeth together might be best achieved by activation of some motor units in the inferior head of the right lateral pterygoid, some motor units in the left posterior temporalis to prevent the left side of the mandible moving forward, and some units in the left masseter and anterior temporalis to help pull the mandible to the left side and to keep the teeth together while doing so. The activation of these motor units will produce a force on the mandible that moves the jaw to the left side. The important point to note is that the entire muscle does not have to become activated to generate the forces for the task at hand. This feature of muscle activation that different parts of a muscle become active for different tasks may be a reason why muscle tenderness can become localized within a muscle if these regions become overworked or strained for some reason.

The pennate arrangement of the muscle fibers together with fiber type composition and selective activation within the masticatory muscles means that there are a wide range of force vectors and durations that can be generated at different locations within the muscle and which enables functional heterogeneity to contribute to the generation of a wide range of mandibular tasks. Generation of contraction forces is complex, and while underpinned by the Henneman size principle where motor units are activated in order of size, other factors including selective activation of regions of a muscle and the rate of motor unit activation are important contributors.

### 3.1.2 Somatosensory Receptors

The orofacial tissues (e.g., facial skin, intraoral mucosa, periodontal ligaments, muscles, temporomandibular joints—TMJs) are extensively supplied with somatosensory receptors that transduce the energy from a physical stimulus (e.g., mechanical, thermal) on the orofacial tissues into action potentials that travel along the nerve fibers to which they are connected. This information enters the brain and is used for perception as well as motivational, affective, and cognitive functions. The information also plays an important role in the control of orofacial movements. Orofacial somatosensory receptors have been extensively reviewed (Capra 1995; Sessle 2006, 2016).

All movements are critically dependent on sensory feedback in order for them to be executed properly. Take, for example, the difficulties encountered with properly coordinated movements of the tongue and lips during mandibular nerve block local anesthesia targeting the sensory nerves to the teeth, bone, lips, and tongue. The *somatosensory* system refers to that part of the sensory system that processes information about touch, pressure, pain, temperature, position, and movement applied to the skin, mucosa, teeth, muscles, or TMJs. The word was coined to distinguish it from other forms of sensory information that is processed by the visual, auditory, and vestibular sensory systems. In the somatosensory system, stimuli (e.g., touch, pressure, pain, tem-

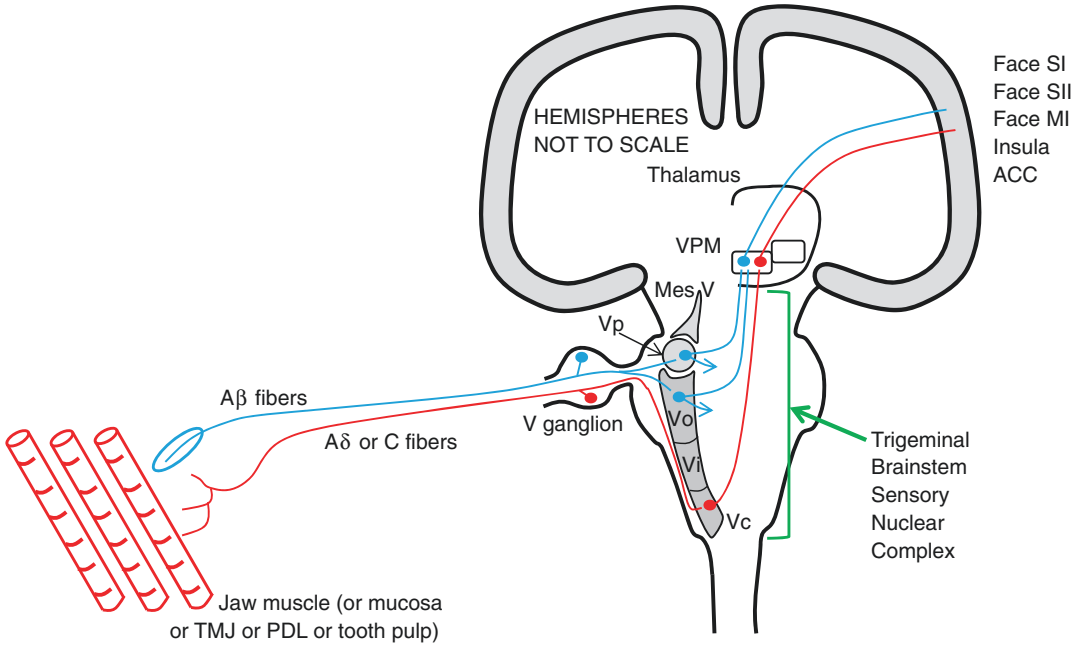


**Fig. 3.4** This shows the basic somatosensory pathway for transmitting information about touch, pressure, pain, temperature, position, and movement from the orofacial area. A section of muscle is shown on the left, but any orofacial tissue can be substituted here (tooth pulp afferents may be nociceptive only). Most somatosensory information travels as action potentials along axons toward the trigeminal brainstem sensory nuclear complex (TBSNC) where the axons terminate via synapses on 2nd order neurons. *Blue* pathways are for pathways (along Aβ fibers) conveying information about non-noxious stimuli (e.g., touch, pressure) and which mainly terminate on 2nd order neurons in the more rostral (*upper*) parts of the TBSNC. *Red* is for pathways (C fibers) conveying nociceptive information and which mainly terminate on 2nd order neurons in the more caudal (*lower*) parts of the TBSNC. *TMJ* temporomandibular joint, *PDL* periodontal ligament, *V* trigeminal, *Vc* subnucleus caudalis of TBSNC, *Vi* subnucleus interpolaris, *Vo* subnucleus oralis, *Vp* principal sensory nucleus of V, *Mes V* mesencephalic nucleus of V, *VPM* ventroposteromedial subnucleus of the thalamus, *SI* primary somatosensory cortex, *SII* secondary somatosensory cortex, *MI* primary motor cortex, *ACC* anterior cingulate cortex

perature changes) are transduced by mechanoreceptors, nociceptors, and thermoreceptors into action potentials that pass mainly through the trigeminal nerve to enter the brainstem (Fig. 3.4).

#### 3.1.2.1 Nociceptive (i.e., Pain-Related) Information

A noxious stimulus at the periphery (e.g., overstretching a masticatory muscle or the TMJ) will be transduced by the muscle and/or the TMJ nociceptors into action potentials that will pass along Aδ and C afferent nerve fibers. The axons of these nerve fibers pass through the trigeminal ganglion, and this nociceptive information descends to terminate via synapses on 2nd order neurons within the subnucleus caudalis (Vc) of the trigeminal brainstem sensory nuclear complex (TBSNC; see Fig. 3.4). The terminals of these primary afferent nociceptive nerve fibers release neurotransmitters (e.g., substance P, glutamate) which bind to receptors (e.g., neurokinin receptors; *N*-methyl-D-aspartate (NMDA) receptors) on the membranes of the 2nd order neurons; the cell body of a 2nd order neuron is represented as a small red dot within the subnucleus caudalis in Fig. 3.4. When the neurotransmitter binds to these receptors, there is an influx of positive ions into the 2nd order neuron, which if large enough causes excitation of the neuron in the form of action potentials which travel along the axon of the 2nd order neuron. The properties of these neurons as well

as the pathway ascending to higher centers will be discussed in section 3.2.

It is worth mentioning here that the TBSNC also receives somatosensory input from other cranial nerves, such as the VII, IX, X, and XII nerves and upper cervical nerves. This convergence of input from these other sites may contribute to some of the referral pain patterns observed in patients with pain, e.g., angina referring to the left mandible, the pain of temporomandibular disorders (TMD) referring to the neck.

It is also important to note that only some of the Aδ and C fibers convey nociceptive information, as other Aδ and C fibers are for sensory and motor autonomic functions (see below). The Aδ nociceptive afferents are fast conducting and are responsible for the first and sharp pain experienced following an initial noxious stimulus, e.g., pinprick. The C nociceptive afferents are much slower conducting and are responsible for the slow and dull pain that is experienced several seconds after an initial noxious stimulus. Under inflammatory conditions such as with damaged muscles or a mucosal ulcer, local immune cells at the site release a range of chemicals (e.g., bradykinin, H+, nerve growth factor (NGF), cytokines) that sensitize the terminals of the nociceptive afferents. These terminals can now become activated even with non-noxious stimuli, such as touching an ulcer or an area of sunburn, or normal muscle contractions during normal mandibular movements in patients with myalgia. The result of this is a sensation of pain in response to normally non-painful stimuli. This phenomenon is called *allodynia*. These sensitized nociceptive somatosensory afferents also can generate many more action potentials in response to a noxious (i.e., painful) stimulus, and the term *hyperalgesia* refers to an increased pain response to a normally painful stimulus. These changes to the excitability of the nociceptive afferent terminals are part of what is called *peripheral sensitization*. One mechanism whereby nonsteroidal anti-inflammatory (NSAID) drugs, such as aspirin, exert their analgesic affects is through interfering with the process of peripheral sensitization. With healing, this peripheral sensitization usually resolves, and, clinically, the allodynia and hyperalgesia also resolve, although with chronic pain (e.g., persistent arthritis, neuropathic pain) these may persist. There is also some evidence for sex differences in these peripheral sensitization mechanisms (Cairns et al. 2014). The increased nociceptive barrage of action potentials associated with peripheral sensitization (particularly along C nociceptive fibers) is also thought to contribute to neuroplastic changes in the brain, and this is termed *central sensitization* (see below).

#### 3.1.2.2 Information About Touch and Pressure

Information about touch, pressure, position, and movement is conveyed mostly by the larger diameter, faster conducting nerve fibers called Aβ fibers (blue fibers in Fig. 3.4). Many of these fibers are connected with mechanoreceptors located within the mucosa, skin, periodontal ligaments, muscle spindles, and TMJ capsule, and these mechanoreceptors are mostly exquisitely sensitive to touch, pressure, and stretch stimuli applied to the tissues. Food contacting the mucosa or the teeth or the maxillary teeth contacting the mandibular teeth as in chewing will activate mucosal and periodontal mechanoreceptors and result in action potentials travelling along these Aβ fibers in the trigeminal nerve to enter the brainstem. Movement of the mandible can also activate mechanoreceptors in the TMJs, muscle spindles, as well as mechanoreceptors in the facial skin and intraoral mucosa (see below). Mandibular movements are therefore associated with a barrage of somatosensory information that travels along many afferent nerves that enters the brainstem and into the TBSNC (Lund and Olsson 1983).

The axons of these nerves conveying non-noxious information (blue lines in Fig. 3.4) terminate on 2nd order neurons mostly in the more rostral parts of the TBSNC, such as the principal sensory nucleus (Vp) and subnucleus oralis (Vo) (see Section 3.2). These 2nd order neurons send their information via the thalamus to higher centers for the perception of touch, pressure, and stretch of orofacial tissues at the periphery and

also for motivational, affective, and cognitive functions. Some of the information, particularly from muscle spindle afferents and TMJ mechanoreceptors, can be used for kinesthetic perception (i.e., mandibular position sense or proprioception). Periodontal, muscle spindle, and TMJ afferents appear to convey information that plays a particular role in interdental size discrimination and for the modulation of motor activity.

Periodontal mechanoreceptors are particularly important and have been extensively reviewed (Trulsson 2007; Trulsson et al. 2012). These mechanoreceptors are located in the periodontal ligaments around the roots of the teeth, and they generate action potentials when forces are applied to the teeth. They signal the magnitude and also the direction of the forces applied to the teeth from tooth-to-tooth contact and also food-to-tooth contact or tongue-to-tooth contact. They also assist other mechanoreceptors (e.g., muscle spindles and possibly TMJ mechanoreceptors) in providing interdental size discrimination. Most individuals are able to detect between 10 and 35 μm (i.e., less than the thickness of a hair) between the teeth (Dubner et al. 1978).

Loss of teeth means therefore a loss of periodontal mechanoreceptors and therefore a loss of the perceptual and motor functions performed by these mechanoreceptors. The somatosensory and motor systems of patients with partial and complete dentures and patients with implant-supported prostheses will therefore be more reliant (or totally reliant if all teeth have been lost) on other orofacial receptors and particularly those that may be less efficient in providing reliable information as to tooth contacts. Thus, in partial and complete denture patients and patients with implants, activity in muscle spindle and TMJ mechanoreceptors as well as mucosal and even cutaneous mechanoreceptors will likely be used by the somatosensory system to take over largely or completely the role of periodontal mechanoreceptors in the perception of tooth contacts as well as in modulating motor activity as in chewing (Klineberg and Murray 1999; Trulsson 2007; Trulsson et al. 2012).

#### 3.1.2.3 Information About Position and Movement: The Muscle Spindle, the Golgi Tendon Organ, and TMJ Mechanoreceptors

Muscles not only have receptors within them for pressure, pain, and temperature, but they also have sophisticated receptors that provide information about their length and how fast their length is changing, as well as the force they are generating. The muscle spindle, located in series with the main fibers of the muscle, provides information about length and length change; and the Golgi tendon organ, located at the end of the muscle fibers before the fibers insert into the bone or tendon, provides information about the forces generated by muscles.

The muscle spindle is a very complicated and very sensitive sensory receptor, and it provides detailed information about length and velocity changes in a muscle over the entire working range of the muscle. It can detect micrometer changes in length. Such a sensitive receptor would easily saturate over the wide range of length changes that most muscles operate if the muscle spindle did not have a system to maintain its optimal sensitivity to avoid saturation. The muscle spindle does indeed have such a system so that it can provide high sensitivity to length and rate of length change throughout the full range of mandibular movements. This maintenance of optimal sensitivity is achieved by the γ-motoneuron innervation of muscle spindles, and the phenomenon is illustrated in Fig. 3.5.

Muscle spindle sensitivity is optimized for all lengths of a muscle which means that the muscle spindle can provide detailed information on lengths and velocities over a wide range of muscle lengths. During a muscle contraction, both α- and γ-motoneurons are activated, and this is termed α-γ-coactivation. The α-motoneurons cause contraction of the main (extrafusal) muscle fibers and are responsible for the force produced by muscles (Fig. 3.5). There is added complexity here in that all muscle spindles have their own motor supply to specialized muscle fibers located within the muscle spindle, and these fibers are called intrafusal muscle fibers. These intrafusal

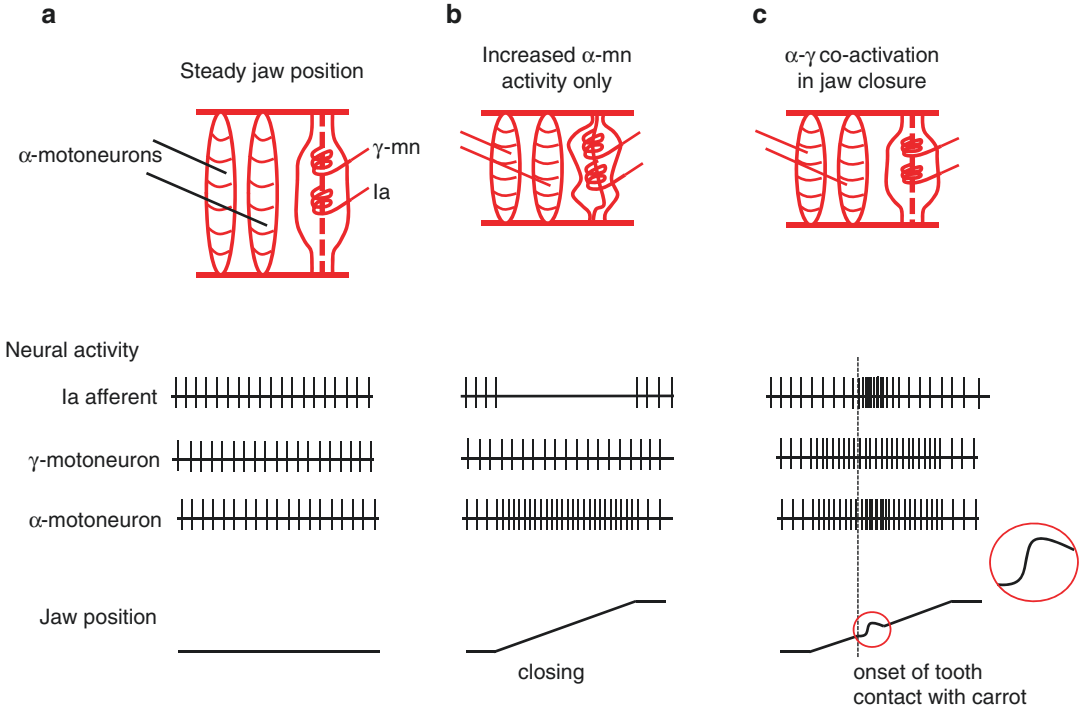


**Fig. 3.5** The *top diagram* in each panel (**a**, **b**, **c**) represents the medial pterygoid muscle showing two extrafusal muscle fibers (innervated by α-motoneurons) and a muscle spindle that contains one intrafusal muscle fiber (continuous *dashed line*; innervated by a γ-motoneuron) supporting the mandible. The sensory part of the muscle spindle is the Group Ia primary afferent that responds to the length and changes in length of the muscle spindle; there are also Group II sensory endings (not shown). Panel (**a**) shows the normal α-γ-coactivation that occurs in any contraction so that α-motoneurons are activated (each short *vertical line* in the neural activity traces represents a single action potential) to induce extrafusal muscle fiber contraction. The simultaneous γ-motoneuron activation results in a slight stretch of the intrafusal muscle fibers so that there is a continuous barrage of action potentials along the Ia afferents from the muscle spindle; these Ia afferents are therefore able to encode or signal any changes in muscle length. Panel (**b**) shows an artificial situation where only α-motoneurons increase their firing to cause a muscle contraction during mandibular closing. The absence of an increased activity in the γ-motoneurons leads to a reduction in the tension within the muscle spindle, and the Group Ia afferents cease to fire action potentials for the duration of the contraction (top neural activity traces, (**b**)). During this period, the Ia afferents are unable to provide any information about unexpected changes in muscle length, and in effect the sensory function of the spindle becomes disabled. Panel (**c**) shows the normal operation of a muscle spindle during a muscle contraction with α-γ-coactivation. The intrafusal muscle fibers contract at the same rate as the extrafusal muscle fibers to maintain the tension at the terminals of the Ia afferents so that they maintain their firing and are able to respond to and signal irregularities in the movement. Contact with a hard nut in a muffin, for example, causes a brief cessation in mandibular closing which stops muscle shortening. However, the γ-motoneuron activity continues to increase and thereby leads to a stretch of the central terminal region of the intrafusal muscle fibers and then a resultant increase in activity of the Ia afferents. As these Ia afferents are connected to α-motoneurons via a monosynaptic reflex arc, the increased Ia afferent discharge causes a very fast, reflex increase in α-motoneuronal activity and an increase in muscle activity to help overcome the increased resistance encountered because of the nut in the muffin. Therefore, this mechanism of α-γ-coactivation maintains the sensitivity of the muscle spindle throughout a muscle contraction, and the spindle is therefore always able to detect small changes in muscle length irrespective of the length of the muscle

muscle fibers are driven by the γ-motoneurons. The γ-motoneurons are activated at the same time as the α-motoneurons, and they cause contraction of the intrafusal muscle fibers within the muscle spindle and therefore maintain the sensitivity of the spindles as the muscle and spindles shorten. Figure 3.5 explains how this comes about.

It should be noted that noxious input to the masticatory muscles can influence the sensitivity of spindles to muscle length changes, so that

there could be an increase or decrease in activity. This modulation appears to be mediated by small-diameter muscle afferents and transmission of nociceptive input to the trigeminal γ-motoneurons and likely is protective by a coordinated excitation or inhibition of motoneurons to promote rest of the injured site (Capra et al. 2007).

The information from the muscle spindles and from the Golgi tendon organs is used to provide a continual flow of data indicating the lengths and rates of length change and forces generated by groups of muscle fibers throughout the muscle. Temporomandibular joint mechanoreceptors are also thought to provide some information regarding joint position although their role may be less important than other mechanoreceptors.

### 3.1.3 Mandibular Movements and Masticatory Muscle Activity

The anatomy of the TMJ is described in detail in Chap. 2. Basic mandibular movements are also described in Chap. 4. The following will briefly review some aspects of mandibular movements and masticatory muscle activity during mastication.

Mastication in the human is not a simple open–close mandibular movement. Animals with large cuspid teeth have such hinge-like mandibular movements. Because of our small cuspid teeth, however, as well as the ability of our mandible to translate forward as well as rotate, masticatory mandibular movements are characterized by varying degrees of lateral displacement particularly during the grinding movements associated with crushing food. As indicated above, these mandibular movements are controlled by motor units in many of the masticatory muscles, so that command signals from the brain do not "think" in terms of which muscles to activate but rather "think" in terms of activating those combinations of motor units, wherever they may be located, that are biomechanically best suited to generate the force vector required for that particular mandibular movement. For example, a grinding movement of the teeth against each other as food is crushed between the teeth would require motor units in parts of the masseter and medial pterygoid muscles on the working side, as well as motor units in the non-working side muscles including the temporalis and masseter muscle. As described above, the entire muscle would not become active in the generation of this movement but only those motor units that are biomechanically best suited for the generation of the force vectors needed. Furthermore, even as the grinding movement progresses, there may be changes in the numbers and locations of motor units recruited to ensure that motor units are activated that are best suited biomechanically for the changing force vectors required to complete the grinding movement. Other mandibular movements will use different combinations of motor units dispersed throughout the masticatory muscles. These movements demand a set of muscles with a complex architecture that allows higher centers of the brain to select motor units that are best oriented in relation to the demands of the movement required.

Dentists have often had an interest in mandibular movements and have described these movements with the use of devices such as pantographs and other jaw-tracking devices. These systems typically provide kinematic information of a single point, by usually recording the movement of the anterior midline of the mandible at the mandibular mid-incisor point. As the mandible is a three-dimensional object, these single point tracings may therefore provide misleading information if used for diagnostic purposes or in the evaluation of treatment outcomes. Furthermore, descriptions of the mandible's movement have not aided clinical diagnosis or management beyond simple range of movement information (i.e., opening, lateral, and protrusive directions) obtained from routine clinical assessment. Attempts have also been made to use the electrical activity of muscles, electromyography, in clinical diagnosis and/or treatment. Unfortunately the recording of electromyographic (EMG) activity from human participants provides data that is highly variable between participants irrespective of whether there is a clinical diagnosis of pain or not. As a diagnostic

tool, like kinematic recordings, electromyography simply does not possess the required sensitivity and specificity to allow clinicians to provide an aid to diagnosis. It is worth quoting from the American Association for Dental Research policy statement on TMD: *the consensus of recent scientific literature about currently available technological diagnostic devices for TMD is that, except for various imaging modalities, none of them shows the sensitivity and specificity required to separate normal subjects from TMD patients or to distinguish among TMD subgroups* (Greene 2010).

#### 3.1.3.1 Masticatory Mandibular Movements

Masticatory movements are complex and consist of mandibular, facial, and tongue movements that are driven by masticatory, facial, and tongue muscles as mentioned below. The facial and tongue muscles are involved because the lips, cheeks, and tongue help control the food bolus in the mouth and keep the food contained over the occlusal table for effective comminution (the effective reduction of the size of the food bolus).

Masticatory mandibular movements usually occur well within the classical border movement pathways except when the mandible approaches or makes tooth contact toward the end of chewing. In the frontal plane, the masticatory cycle is described as "teardrop" in shape. At the beginning of opening, the mid-incisor point moves first downward, and at the end of opening, it moves laterally and upward toward the working side (or chewing side). The mid-incisor point then moves upward and medially, and the food is crushed between the teeth.

While these mandibular movements during chewing are the classical description, the masticatory movements tend to be highly variable from cycle to cycle in a subject chewing the same or different foods and from subject to subject (Lund 1991). Part of this variability relates to the changing consistency of the food bolus from cycle to cycle as the food breaks down. The movement of the mandible toward intercuspal position is less variable. The masticatory muscles must move the mandible precisely toward the teeth at the end of the chewing cycle, so that the teeth glide smoothly along cuspal inclines and generate the required force to crush and break down the food. Mechanoreceptors (particularly periodontal, but also muscle spindle afferents; see above) provide a continual source of afferent input to the CNS to ensure that the chewing cycle is harmonious with existing tooth guidance (see above). These modulatory effects on motoneuronal activity will be mediated via local reflex circuits and also by modulatory influences on the masticatory central pattern generator (CPG), as well as providing modulatory influences on higher motor centers such as the motor cortex (see below) (Lund 1991).

There are several different phases of each masticatory cycle (Trulsson et al. 2012). The preparatory phase is the phase in which the mandible, tongue, lips, and cheeks prepare the bolus for effective food comminution. The reduction phase is the phase where food comminution is associated with salivary flow and mix of food and saliva, and the pre-swallowing phase is where the comminuted food is brought together with saliva as a bolus, in preparation for swallowing.

There are a number of intrinsic and extrinsic factors responsible for variations in the masticatory cycle (Woda et al. 2006). Intrinsic factors include age, gender, and dental status, and extrinsic factors include the hardness, rheological properties (plasticity/elasticity), and size of the food. For example, harder foods of larger size are associated with more cycles of longer duration and higher EMG activity, while older age and tooth loss are also associated with more cycles of longer duration and higher EMG activity (Van der Bilt 2011; Woda et al. 2006). A significant factor in modifying the chewing cycles would be changes in the somatosensory inputs associated with foods of different sizes, hardness, and textures (Van der Bilt 2011; Woda et al. 2006). The activity in periodontal, muscle spindle, mucosal, and possibly TMJ mechanoreceptors associated with different foods can modify, as noted above, motoneuronal activity via brainstem and higher pathways.

It is noteworthy that the tongue is largely made of muscle which during mastication positions the food bolus but does not itself get bitten, usually. The face motor cortex may play an important role here by strongly inhibiting mandibular closing muscle activity during tongue and indeed facial movements that move the food bolus over the occlusal table. The tongue is most active during the opening phase of the chewing cycle when food is required to be collected and repositioned for effective comminution on the occlusal table.

The movement of the condyle and disc during normal mandibular movements is complex. The lateral pterygoid muscle plays an important role because it is a major contributor to opening, lateral, and protrusive jaw movements and inserts near the TMJ, with the inferior head inserting exclusively into the condylar neck and the superior head inserting largely into the condylar neck. Some fibers of the superior head do insert into the disc–capsule complex of the TMJ, but the long-held view (still held by some) that the superior head inserts exclusively into the disc is not correct. Further, the view that the superior and inferior heads of the lateral pterygoid muscle exhibit reciprocal patterns of activity is not supported by current data (Murray et al. 2007; Murray 2012). The superior head and the inferior head of the lateral pterygoid muscle have very similar functions in that both are active in contralateral, protrusive, and open–close jaw movements. However, there is evidence for functional heterogeneity within each head of the lateral pterygoid muscle so that it appears that the brain is able to activate independently those motor units of each head of the muscle to provide a force vector onto the condyle that is biomechanically best suited to generate the movement required.

Changes to the occlusion may have an influence on the movement of the mandible and the TMJ and the function of the masticatory muscles, and these effects have been extensively reviewed (Van der Bilt 2011; Woda et al. 2006). Thus, restoring teeth, in such a way that necessitates a change to the normal pathways of a chewing cycle, will lead to different levels of firing of orofacial afferents (e.g., periodontal afferents, but also muscle spindle and possibly TMJ mechanoreceptors and Golgi tendon organs). This information will feed back to the CNS (see below) and can cause a variety of changes to neural activity, including reflex changes in muscle activity, changes in the activity of the CPG controlling mastication as well as changes in the activity of the primary motor cortex. These changes in neural activity brought about by an altered afferent input can result in immediate functional changes and can also contribute to longer-term structural changes. The resultant effects will be a change to the activity of particular motor units, in particular subcompartments of muscles, so that the appropriate modification to the chewing cycle can occur so as to accommodate to the change in the occlusion. The new chewing cycle will now accommodate to the changed occlusion unless the interference is too large and beyond the adaptive capacity of the CNS and muscles. Of note is that normal tooth contact occurs for only approximately 10–20 min daily with eating and swallowing (Sheppard and Markus 1962) and together with neuroplasticity (the ability of the nervous system to adapt; see below) results in an individual tending to adapt to occlusal changes rather rapidly in the majority of the population; some individuals may not adapt as well, and this lack of adaptability may be a factor contributing to impaired jaw function.

## 3.2 Physiology of the Masticatory System: Central Aspects

Up to now, we have been mostly describing the complex peripheral apparatus that allows us to perceive our environment and to generate mandibular movements. How does the brain process the somatosensory information from the periphery and how does the brain drive the muscles to generate the range of movements and forces possible by the orofacial motor system? To answer these questions, the following will review the central pathways for the processing of somatosensory information as well as the central pathways responsible for the generation of movements.

### 3.2.1 Processing of Somatosensory Information Within the Brain

Low-threshold, non-noxious stimuli applied to mechanoreceptors in the orofacial area result in action potentials travelling along nerves to terminate on 2nd order neurons mostly within the more rostral components of the TBSNC such as the Vp and the Vo. Other receptors in the orofacial area respond to innocuous temperature changes (hot and cold thermal receptors), and they terminate on 2nd order neurons in the subnucleus caudalis.

As shown in Fig. 3.4, this information is relayed through the thalamus (the ventroposteromedial subnucleus) to terminate within the face region of the primary somatosensory cortex (face SI), the face region of the secondary somatosensory cortex (face SII), as well as other centers such as the insula (Haggard and de Boer 2014). These projections to face SI and face SII are likely important for our perception of tooth contacts. The possible projections to the insula may play a role in the awareness associated with orofacial sensory stimuli, for example, the pleasurable aspects associated with the enjoyment of food textures, or an excessive awareness of occlusal contacts.

Somatosensory information can be used for the local modulation of motor activity through reflex pathways and via the masticatory CPG. When encountering harder food during chewing, the harder food will activate periodontal mechanoreceptors, and this information can be used not only for fast reflex increases in activity in parts of the masticatory muscles but also for modulation of the masticatory CPG so that the mandible is moved so as to generate the required forces between the teeth to crush the food with greater consistency. These pathways from the 2nd order neurons for fast reflex changes in muscle activity and also for modulation of the masticatory CPG are indicated by the blue arrows arising from the 2nd order neurons within Vp and Vo in Fig. 3.4.

Orofacial somatosensory information ascends to higher centers of the brain such as the face region of the primary motor cortex (face MI) for the modulation of voluntary motor activity. For example, we can voluntarily increase the force on an object between the teeth (e.g., food bolus, cotton roll), and this ability would require continual monitoring of the activity of periodontal afferents, particularly, that would be fed back to the face MI and face SI and allow us to finely adjust the amount of force exerted.

In the previous section describing peripheral aspects of nociceptive somatosensory processing, it was noted that primary afferents terminate on 2nd order neurons in the subnucleus caudalis (Vc) of the TBSNC. There are two main types of nociceptive 2nd order neurons. The nociceptive-specific (NS) neurons receive only Aδ or C fiber input conveying nociceptive information that is evoked when noxious stimuli are applied to the receptive fields of these neurons. [A receptive field of a neuron is the region of the skin, mucosa, or deep tissue over which a stimulus can be applied, and the neuron will respond by generating action potentials.] The other type of nociceptive 2nd order neuron is called a wide dynamic range (WDR) neuron, and these neurons not only receive Aδ or C fiber input conveying nociceptive information but also low-threshold non-noxious input conveyed along Aβ fibers, such as tactile input. These WDR 2nd order neurons therefore not only respond by generating action potentials when noxious stimuli are applied to their receptive fields but also can generate action potentials when tactile and other low-threshold inputs are applied to their receptive fields. Another feature of each of these 2nd order neurons is that many receive the so-called convergent somatosensory inputs from a number of different regions of the orofacial area, such as masticatory muscles, the TMJs, tooth pulp, facial skin, mucosa, etc. Under normal physiological conditions, these inputs may be inconsequential and may only become *unmasked* under pathological conditions (see below). This convergence of somatosensory inputs is thought to contribute to the poor localization and referral so characteristic of orofacial pain.

Under conditions where there is long-lasting and/or intense noxious stimulation of the periphery (Mense and Hoheisel 2008; Sessle 2008),

such as a blow to the jaw or stretching of the masticatory muscles as with a prolonged dental appointment, these 2nd order NS and WDR neurons can undergo *central sensitization*. This sensitization consists of neuroplastic changes to these 2nd order neurons that result in increased levels of neuronal excitability. Recent evidence suggests that the glial cells in the vicinity play a key role in these central sensitization processes (Chiang et al. 2011; Sessle 2011b). Since these 2nd order neurons convey nociceptive information to higher centers for perception, then increased levels of excitability can mean that individuals experience *allodynia*, that is, a sense of pain in response to low-threshold input, e.g., tactile input as with lightly touching the injured part. They may also experience spontaneous pain, i.e., pain at rest and without pressing on the injured part. This may be part of the reason for the pain experienced in injured masticatory muscles at rest and why light pressure on the masticatory muscles or normal mandibular movements are associated with pain or worsening of pain. Another good example of allodynia is pain associated with light touch of sunburnt skin.

As indicated above, many of these 2nd order nociceptive neurons also receive convergent input, and these inputs may only become unmasked in pathophysiological conditions where the neurons undergo central sensitization. Under these circumstances, the higher centers of the brain responsible for perception may misinterpret the injury as occurring from the peripheral site innervated by one of the convergent inputs and that may have nothing to do with the original injury. This can be a reason for the spread and referral of pain that is such a characteristic of pain associated with inflammation (Sessle 2008). These processes are likely to play a significant role in the muscle and/or TMJ pain associated with TMD. In most individuals these central neuroplastic changes reverse after the peripheral injury resolves, but in some people the changes may persist and thereby may lead to persistent or chronic pain states. It is not clear why these neuroplastic changes do not reverse in all individuals, but it is thought that genetic and phenotypic (including environmental) factors may play a role in these persistent effects.

There is added complexity in that the activity of these 2nd order nociceptive neurons can be modulated by somatosensory inputs and by descending influences from higher centers. These modulatory influences have been described in terms of the gate control theory proposed by Ron Melzack and Pat Wall in the 1960s (Melzack and Wall 1965). Figure 3.6 outlines some possible pathways involved in the gate control theory. In terms of somatosensory modulation, pain can be alleviated through activation of tactile inputs by rubbing the sore area or by clinical procedures such as pressure/vibration to the lip during an intraoral injection, acupuncture, or transcutaneous electrical nerve stimulation (TENS). These procedures activate low-threshold somatosensory inputs (blue pathway, Fig. 3.6) that act, via inhibitory interneurons (black pathway, insert, Fig. 3.6) in the brainstem, to inhibit (minus sign, insert, Fig. 3.6) the activity of nociceptive 2nd order neurons, that is, to close the gate and suppress the transmission of nociceptive information to higher brain centers where the perception of pain occurs. The gate control theory also includes other modulatory factors, including those coming from higher centers of the brain (such as the periaqueductal gray (PAG), the brainstem raphe system, as well as the limbic system, e.g., amygdala, hypothalamus) and which send descending pathways to these same 2nd order nociceptive neurons and can have either inhibitory effects (minus sign, insert, Fig. 3.6) or excitatory effects (plus sign, insert, Fig. 3.6). The inhibitory effects can come into play in situations where the peripheral injury carries little emotional significance given the situation, for example, a football player injuring his/her wrist during an intense game and only becomes aware of the injury after the game. In this situation, powerful descending pathways from higher brain centers are inhibiting the activity of the 2nd order neurons that would be receiving a barrage of nociceptive activity from the injured wrist. This intrinsic pain inhibitory system also operates in more normal situations and likely contributes to our natural ability to have some control over our experience of pain. It also may contribute to the effectiveness of some pain-relieving approaches, such as acupuncture and TENS that appear capable of recruiting these

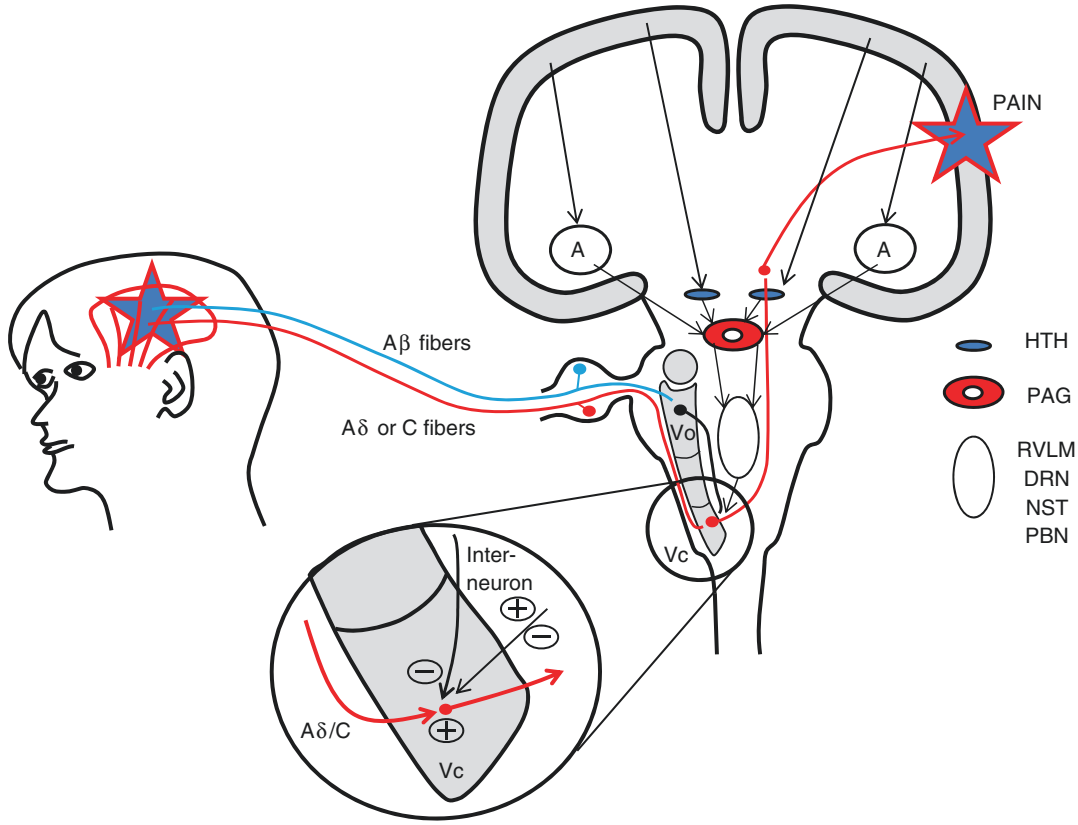


**Fig. 3.6** This shows the two basic components of the gate control theory. Information about a noxious stimulus, in this case, a blow to the temporalis muscle, is conveyed by Aδ and C afferent fibers to terminate on 2nd order neurons (see *inset*) in the subnucleus caudalis of the trigeminal brainstem sensory nuclear complex. The nociceptive information is transmitted to higher centers for the conscious perception of pain (indicated by the *star*). The synaptic connections between the nociceptive afferent fibers and the 2nd order neurons are subject to powerful modulating influences from two sources. The first is from low-threshold Aβ fibers which can be activated by rubbing the sore area. The Aβ fibers activate inhibitory interneurons (black connection between Vo and Vc) that exert inhibitory effects on the synapses between the Aδ and C afferent fibers and the 2nd order neurons. The other modulatory influences come from higher centers and these can be inhibitory or excitatory. The inhibitory pathways are operative under most circumstances of acute pain and act to dampen the nociceptive transmission to higher centers. These descending pathways may be dysfunctional in certain orofacial pain states, such as some TMD. Excitatory effects can also occur and can promote the transmission to higher centers of nociceptive information, and these effects may operate in, for example, the fearful dental patient. The transmission to higher centers of nociceptive information may in fact be facilitated in these patients. *HTH* hypothalamus, *PAG* periaqueductal gray matter, *RVLM* rostroventrolateral medulla, *NST* nucleus of the solitary tract, *PBN* parabrachial nucleus, *A* amygdala, *Vo* subnucleus oralis, *Vc* subnucleus caudalis, + excitatory connection, – inhibitory connection

pathways (as well as through peripheral mechanisms as mentioned above).

Not only can the "gate" be closed, it appears that it also can be "opened up," and this may occur in fearful situations such as the highly anxious dental patient. In this situation, descending influences appear capable of reducing the threshold of firing of these nociceptive 2nd order neurons so that they more easily respond to even the slightest nociceptive stimuli or even non-nociceptive input (plus sign, insert, Fig. 3.6). This emphasizes that pain is an individualized personal sensory and emotional experience and that assessment and management need to consider these multidimensional aspects.

These axons of these 2nd order nociceptive neurons mostly cross the midline and ascend to terminate on 3rd order neurons within the

thalamus. Specifically for the trigeminal system, they terminate within the ventroposteromedial (VPM) subnucleus but also other nuclei, such as the medial thalamic nuclei. These 3rd order neurons are activated in the same way and have similar properties as neurons within the TBSNC, and they then send their axons to higher centers such as the face region of the primary somatosensory cortex (face SI) and secondary somatosensory cortex (face SII) and also other brain regions such as the insula, cingulate cortex, and prefrontal cortex. Only when this information enters and is processed by these and other cortical regions, do we interpret the nociceptive information as pain in the region of the periphery. Many areas of the brain become active with somatosensory receptor activation, for example, noxious stimulation of the masticatory muscles results in activity with face SI and SII that likely contributes to the sensory-discriminative aspects of the painful experience. Activation of other regions of the brain such as the insula and anterior cingulate cortex appears to be responsible for the motivational–affective dimensions of the pain experience. Many of these regions can also become active in chronic pain states (Apkarian et al. 2011; Lin 2014).

The axons of the 2nd order neurons also pass to regions of the brainstem such as the reticular formation and other parts of the brainstem for involvement in autonomic reflex responses such as salivation in response to taste and texture of food, as well as cardiorespiratory changes to orofacial noxious and non-noxious (e.g., textures, taste of food) stimuli. Some of these axons also terminate locally around the TBSNC for the generation of reflex responses in response to nociceptive and non-nociceptive stimuli (see below) and also send their inputs to the CPGs for mastication and swallowing.

It is also worth noting that not only can neuroplastic changes occur in association with nociceptive inputs (discussed above under central sensitization) but neuroplastic changes can also occur in 2nd order and higher neurons responsible for the transmission of non-nociceptive information to higher centers. These changes can be functional changes in neuronal activities as well as changes in neuronal connections and pathways, and they appear to be responsible for the learning that occurs in association with adaptation to new dentures and new occlusal schemes (Avivi-Arber et al. 2011; Sessle 2011a; Sessle 2016).

### 3.2.2 Generation and Control of Orofacial Movements by the Brain

In describing how the brain generates and controls movements, it is helpful to classify the movements that we can produce.

Orofacial movements can be classified into:

1. Voluntary movements such as opening and closing the mandible, moving the mandible forward and backward, moving the mandible in speech, etc.
2. Reflex movements such as the jaw-jerk reflex and the jaw-opening reflex
3. Rhythmical movements such as mastication and swallowing

#### 3.2.2.1 Voluntary Movements

In general terms, voluntary movements are movements that we voluntarily perform, such as playing the piano, speaking, making an alginate impression, and moving the mandible to one side or the other. All these movements are driven by the primary motor cortex (termed MI) as well as higher motor cortical areas such as the supplementary motor area (SMA) and the premotor cortex. The face MI lies just in front of the central sulcus (Fig. 3.7), and the face MI initiates and produces voluntary movements of the face, mandible, and tongue. When a person moves the tongue forward and to the right side and opens their mouth, the basal ganglia select a set of programs within the SMA and the premotor cortex (area 6) which then send signals to the face MI. These motor programs contain the details of those parts of the face MI to be activated so as to activate the correct combination of motor units within the tongue so as to generate this movement of the tongue to the

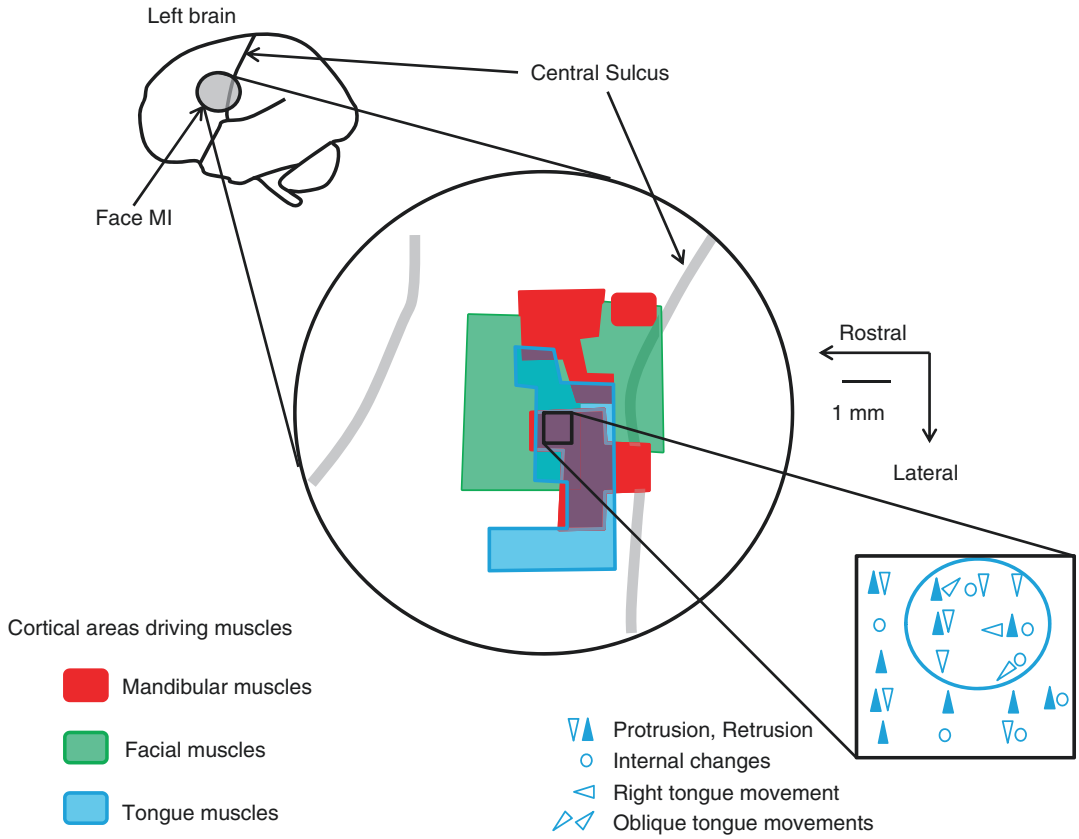


**Fig. 3.7** This figure shows a two-dimensional hypothetical mapping of the organization of the motor representation within the left face primary motor cortex (MI). The diagram at the *top left* is an outline of the left brain. The overlying *circle* covers the face MI and is expanded in the central panel to show regions of the face MI that are responsible for activating α-motoneurons that drive muscle fibers within the masticatory muscles (*red areas*), facial muscles (*green areas*), and tongue muscles (*blue area*). For example, the areas of the face MI covered by the *blue outline* contain elemental cortical zones that send outputs down to hypoglossal α-motoneurons that drive motor units within the tongue. The *black square box* overlying the tongue muscle cortical region is expanded at the *bottom right* to show the fine structure of these elemental tongue zones within the face MI which, when activated, result in activation of tongue motor units leading to different types of tongue movements, as indicated by the *arrowheads* and the *circles*. Note that these elemental movements are represented multiple times in different locations in the face MI, and one particular movement can be close to other elemental movements at these different locations. It is thought that the higher centers of the brain can select different combinations of tongue output zones to allow the generation of more complex movements (similar to the generation of more complex sounds, as when playing chords on a piano). A small section of the tongue motor cortex is shown in Fig. 3.8 to show the neural connections from the face MI down to hypoglossal motoneurons. There is a similar complexity of organization for face and mandibular movements

right side. The MI is then responsible for activating the required motor units to produce this tongue movement to the right side.

The face MI consists of specific elemental zones for the production of specific elemental movements, and this organization is illustrated in Fig. 3.7. Note that there is a lot of overlap of mandibular, facial, and tongue elemental zones, and this overlap is thought to facilitate the combined activation of mandibular, facial, and tongue movements by higher centers of the brain driving the face motor cortex. For example, most mandibular movements involve not just a movement of the mandible but also there are usually associated facial and tongue muscle activations that accompany the mandibular movements.

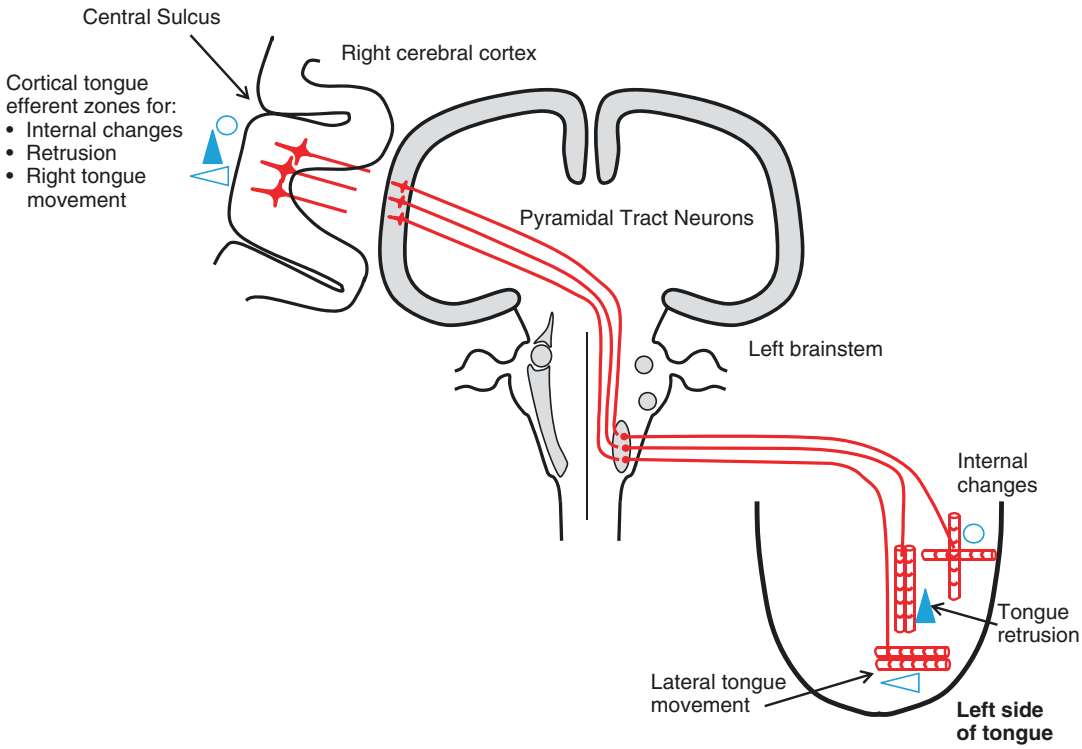


**Fig. 3.8** The figure shows a stylized brain in the central panel. A magnified region of the face motor cortex (face MI) in cross-section is shown on the left with three elemental tongue zones for the generation of three elemental tongue movements, namely, internal changes to the tongue shape, tongue retrusion, and right tongue movement. Each elemental tongue movement is driven by pyramidal tract neurons (only one shown for each elemental tongue zone) that send fibers in the pyramidal tract that cross to the other side to synapse directly or indirectly (via interneurons) onto α-motoneurons within the hypoglossal motor nucleus. Note that in this diagram, only one pyramidal tract neuron is connected to one α-motoneuron and two muscle fibers for the generation of each type of elemental tongue movement, but in reality, there are many of each with extensive connections. The α-motoneurons then activate the relevant muscle fibers for the generation of the required tongue movement, in this case a tongue movement to the right, tongue retrusion, and an internal change to tongue shape

Figure 3.8 shows three selected elemental tongue zones and how they are represented by pyramidal tract neurons that send fibers in the pyramidal tract to synapse directly or indirectly (via interneurons) onto α-motoneurons within the hypoglossal motor nucleus.

The face MI therefore contains an extensive representation of elemental movements for all the muscles of the face, mandible, and tongue. The face MI therefore can be considered to be the "keys of a piano" that the higher motor centers *play* in order to allow the generation of the required voluntary movement.

As described above, Fig. 3.4 shows the somatosensory pathway conveying information to the face SI. Another complexity is that not only does the face SI receive somatosensory information from the periphery, but there is also an extensive somatosensory input to neurons in the face MI. For the tongue region of the face MI, for example, many of the neurons in the motor cortex receive low-threshold tactile inputs from the tongue dorsum. This tactile input is thought to play a role in the fine modulation of tongue movements to accommodate quickly to the particular requirements of the tongue movement; for example, with moving food around in the mouth, the motor cortical zones driving motor units in the tongue are greatly assisted by having a continual feedback of the amount of pressure, for example, being exerted by the tongue on the food bolus. There is a similar extensive somatosensory

input from orofacial mechanoreceptors to the facial muscle and masticatory muscle elemental zones. This information would provide continual feedback for the refinement of these movements in voluntary movements of the mandible and face. For example, in the assessment of interdental size discrimination, periodontal feedback will play a very important role in modulating the amount of activation within the masticatory muscle region of the face MI so that the correct level of activation occurs within the masticatory muscle region of the face MI so as to drive the required combination of motor units in the various mandibular closing muscles to achieve the required mandibular closing force for assessment of thickness.

In recent years it has become apparent that the brain can undergo neuroplastic changes. Neuroplasticity refers to the structural and functional changes in the brain in association with motor skill acquisition and learning and also in adaptation to changes at the periphery that result in alterations of sensory inputs. The changes can include unmasking of existing synaptic connections that were previously silent, increases or decreases in the synaptic strengths of existing connections, and development of new neural connections. In the case of the orofacial motor system, these changes can occur following changes to the dental occlusion through loss of teeth, placement of restorations, provision of implants and dentures, and orthodontic tooth movement. It is thought that new dental occlusion leads to alterations in the somatosensory information that comes back into the brain because, for example, if some teeth have been extracted, then there will be fewer afferent neurons conveying somatosensory information from periodontal mechanoreceptors, and therefore there will be less information about the magnitude and direction of forces on teeth as artificial teeth or implants do not have an equivalent periodontal mechanoreceptor innervation. Other receptors may be relied upon more to provide the needed information about the direction and magnitude of tooth contacts, and these may include periodontal mechanoreceptors around any remaining teeth, muscle spindles, Golgi tendon organs, mucosal mechanoreceptors underneath dentures, etc. It is thought that with changes to the occlusion, the motor systems controlling voluntary and rhythmical (see below) orofacial movements will undergo changes in their neural circuitry (i.e., neuroplastic changes) to allow the required mandibular, facial, and tongue movements still to be performed. There is indeed evidence in the human for neuroplastic changes within the sensorimotor cortex following the insertion of implant-supported prostheses in edentulous individuals (Palla and Klineberg 2016). Nonetheless, there is good evidence that the efficiency of the resulting movements may not always be equivalent to the efficiency before the loss of teeth, particularly if most/all of the teeth are lost (Van der Bilt 2011). There are clearly limits therefore to the adaptability of the brain in terms of the neuroplastic changes that can occur, and genetic and age factors likely play an important role in this.

These neuroplastic changes are also thought to be important in more subtle adjustments to the motor system, for example, in allowing an individual's motor system to accommodate to new dentures. Some patients can experience difficulty in accommodating to dentures which are different from the old dentures in terms of vertical dimension, flange contours, occlusal form and position, etc. A feature of neuroplastic changes in the brain is that an older brain appears less able to undergo neuroplastic changes than a younger brain, and the elderly may have trouble adapting to their new dentures, despite being technically acceptable, because of the limited ability of their brains to undergo neuroplastic changes. As a general rule, it is best to minimize any changes to the dental status of elderly individuals to avoid stretching the limited ability of the elderly brain to undergo neuroplastic changes. For example, increases in vertical dimension, as might be recommended in a complete denture patient who has a significantly over-closed vertical dimension, should be done in a staged approach, particularly in the older patient. There is also evidence that pain interferes with the ability of the brain to undergo the neuroplastic changes occurring during skill acquisition. This probably is a reason

why people in pain may not be able to adapt to new dentures or prosthetic devices (Sessle 2016).

The outline above of the neural control of voluntary movements has focused on the motor cortex. Another important component of the motor system is the cerebellum which plays a role in the refinement of movements. A classic test for a cerebellar lesion is to ask the patient to touch an object at arm's length with their finger. A normal healthy person performs this accurately and quickly. A patient with a cerebellar lesion performs this movement slowly and inaccurately and with many mid-trajectory corrections. So the movement can still be performed, but it is very inaccurate. When the motor cortex drives a voluntary movement, it sends a copy of the signal that goes to the motoneurons also to the cerebellum. As the movement is progressing, somatosensory receptors are activated as a normal part of the movement, and this information not only goes to the somatosensory and motor cortices (as mentioned above), but also a copy of the signal goes to the cerebellum. The cerebellum uses both signals, the intended drive signal from the motor cortex and the actual signal from the movement, to work out errors in the movement. Thus when the somatosensory feedback from the part of the body being moved does not match the drive signal from the motor cortex, an error signal is generated that helps to correct the movement by modifying the activity of the motor cortex. Corrections to each movement can also occur via shorter pathways that involve fewer neurons, and many of these pathways are located entirely at the brainstem level. These pathways can be demonstrated clinically by evoking reflexes.

### 3.2.2.2 Reflex Movements

When the word *reflex* is mentioned, we tend to think of the medical physician evoking the knee-jerk reflex by a brief tap to the knee leading to a single motor response. But this is a very artificial situation that does not usually operate as such in normal life—we do not need to tap our knees to allow us to walk! The ability to evoke a reflex simply demonstrates that there are connections between certain somatosensory afferent nerve fibers and certain α-motoneurons. These neural pathways are critically important and are continuously used to refine and modulate both voluntary and rhythmical movements. It just so happens that an artificial reflex response can be demonstrated clinically and in the research setting by selective sudden activation of some somatosensory afferents.

In general, reflex pathways are organized at the brainstem or spinal cord level and generally do not involve higher centers of the brain such as the motor cortex. Therefore information travelling along these pathways at the brainstem or spinal cord level brings about its effects very quickly, and these effects are little modified by voluntary will. In the masticatory muscle motor system, reflexes include the jaw-closing or jaw-jerk reflex and the jaw-opening reflex. These reflexes have been extensively reviewed (Türker 2002).

#### Role of Reflex Pathways in Masticatory Movements

##### Non-noxious Reflex Pathways

Reflex pathways provide a very fast neural circuit whereby somatosensory information from the oral cavity can be used to fine-tune movements (see below) so that they occur in a manner that adapts to the particular loads imposed on the mandible during movement. Of particular importance in the fine control of masticatory movements is the information provided through the activation of periodontal mechanoreceptors and muscle spindles. These mechanoreceptors allow fast feedback (in ~10 ms) that adjusts a movement to overcome small, unpredicted irregularities in an ongoing movement as can occur from unexpected changes in food bolus consistency. The information does not have to go to higher centers (which will take much longer) before the subtle refinement can be carried out. The reflex effects also add smoothness to a movement.

For example, as food is crushed between the teeth, the activation of periodontal mechanoreceptors can cause a reflex *increase* in activity in the mandibular closing muscles to assist in crushing of food. This increase in activity comes about

because low levels of activation of periodontal afferents, as occurs during chewing, facilitates the activation of specific mandibular closing motor units. The effect of this is to generate the appropriately directed mandibular movements to assist, for example, the masticatory muscles in guiding the teeth to crush the food with the correct force and as the teeth slide smoothly past each other during the slow closing phase of chewing.

As described above, muscle spindles are very sensitive to changes in length of the muscle and also play a role in assisting chewing. Also as described above (Fig. 3.5), unexpected changes in length or velocity of contraction are signaled by the muscle spindles which send action potentials into the brainstem. Within about 8 ms of a slowing of closing brought about by encountering harder food (i.e., a nut) within a food bolus, α-motoneurons to the mandibular closing muscles increase their activity to help crush through the nut. This effect, which depends on these reflex pathways, does not involve higher centers (and therefore conscious perception) and therefore is very fast. There is however an awareness of the increase in food resistance, and we can also voluntarily increase the force by activating the mandibular (i.e., jaw) efferent zones in the face MI, but these perceptual and motor effects come well after the fast reflex effects. If higher centers were only involved every time we closed onto harder food within a food bolus, then our voluntary mandibular closing movements would be much slower and less efficient because the pathways to and from the higher centers are much slower than those to and from the brainstem. Therefore muscle spindles allow very fast adjustments to the forces generated by jaw-closing muscles so that these forces are appropriate for the needs of the mandibular movement or mandibular forces at the time required. This fast pathway from muscle spindle Ia afferents to jaw-closing motoneurons is shown in Fig. 3.9.

It is also likely that other mechanoreceptors such as TMJ mechanoreceptors, Golgi tendon organs, and mucosal and possibly cutaneous mechanoreceptors also provide feedback to the motor system possibly individually or in some complex combination given the convergence of this information centrally to help modulate motor unit activity and recruitment to achieve the most optimal chewing cycle.

### Noxious Reflex Pathways

While many orofacial inputs can enhance or modulate muscle activity to assist in mastication as described above, noxious orofacial stimulation generally has a profound inhibitory effect on mandibular closing muscles. For example, sudden high-intensity activation of periodontal afferents results in inhibition of mandibular closing muscles and cessation of the patterned output from the masticatory CPG so that the teeth are not damaged. An immediate cessation of the output from the CPG also occurs with noxious stimulation of orofacial tissues such as when biting the lip or cheek by mistake. We all know how biting the cheek suddenly stops chewing. This occurs via, again, a very fast brainstem-based reflex, the jaw-opening reflex, and this reflex can operate in about 10 ms.

The jaw-opening reflex can be evoked by a variety of types of orofacial afferents. Activity in primary afferent nerve fibers from, for example, mucosal nociceptors, enters the brainstem to contact inhibitory interneurons that then synapse on jaw-closing α-motoneurons and reduce the activity of these motoneurons. At the same time, these same primary afferents send branches to activate other interneurons that are excitatory to mandibular opening muscles, such as the digastric. The overall effect is an opening of the mouth.

Nociceptor activation within muscles can have effects on the sensitivity of muscle spindles with both increases and decreases being noted (Capra et al. 2007). These changes to the sensitivity of muscle spindle afferents in muscle pain may contribute to the deficits in interdental size discrimination as well as the decreases in the force of contraction and irregular chewing cycles noted in TMD patients (Capra et al. 2007).

## Role of Reflex Pathways in Voluntary Closing Movements

When cracking a hard nut between the teeth, there is an initial increase in force when the teeth are contacting the nut and before the nut cracks.

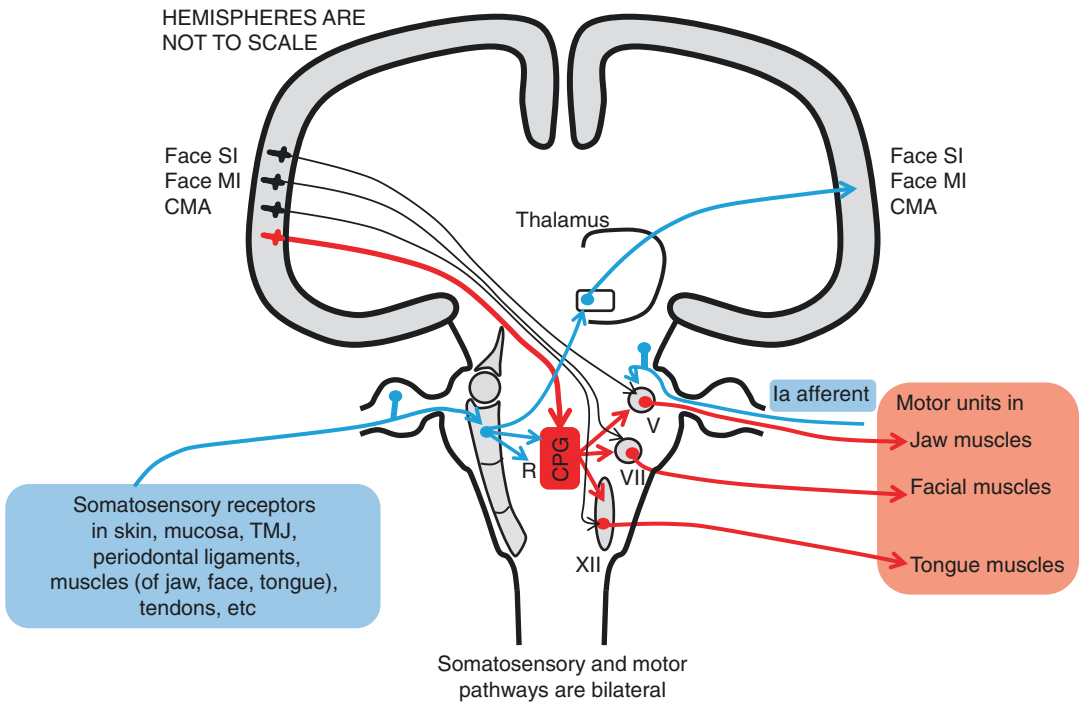


**Fig. 3.9** This figure shows a stylized brain with some important pathways and nuclei for the generation of mastication. Somatosensory nuclei are shown on the left side and motor nuclei on the right side, but in reality the nuclei are on both sides. The masticatory central pattern generator (CPG) is located in the pontomedullary reticular formation and when activated sends the appropriately timed impulses to the various mandibular, facial, and tongue muscle α-motoneurons in the trigeminal (V), facial (VII), and hypoglossal (XII) motor nuclei and thereby to generate mastication. The masticatory CPG can be activated and modulated by descending inputs from higher centers as shown by the *red* pathway from the cortical masticatory area (CMA), face primary somatosensory cortex (SI), and face primary motor cortex (MI). It can also be modulated by somatosensory receptors in the skin, mucosa, TMJ, periodontal ligaments, muscles, tendons, etc., which send afferent nerve fibers to terminate on 2nd order neurons within the trigeminal brainstem sensory nuclear complex; muscle spindle afferent cell bodies lie in Mes V, Fig. 3.4. These 2nd order neurons ascend through the thalamus to higher centers for perception (face SI, face SII, etc.) and also pass to the masticatory CPG for modulation of the masticatory movements to accommodate to the texture and hardness of the food bolus. Other connections (R; Ia afferent) can modulate α-motoneuron activity within mandibular muscles to provide fast adjustments to mandibular muscle activity (e.g., see Fig. 3.5). The direct pathways from the face MI to α-motoneurons to allow voluntary activation of mandibular, facial, and tongue muscles are shown in black. *TMJ* temporomandibular joint

This increase in force is due to two factors. One is the increased α-motoneuron discharge to motor units in masticatory muscles because of voluntary activation from the motor cortex (see Fig. 3.9). The other factor that contributes to increased muscle activity comes from γ-motoneuron activation that usually keeps the intrafusal muscle fibers contracting at the same rate as the main extrafusal muscle fibers to maintain spindle sensitivity (see above). However, the mandible has stopped closing (because of the nut) and the continued γ-motoneuron activation causes the intrafusal muscle fibers to keep shortening, and this results in stretching of the Ia afferent terminals in the center of the spindle (see Fig. 3.5c). This leads to an intense discharge in the Ia afferents that feeds back within about 8 ms to the α-motoneurons so that there are further increases in α-motoneuron activity until the nut cracks. As soon as the nut cracks, however, there needs to be a mechanism that prevents the opposing teeth crashing together and possibly causing damage. This is also achieved in a number of ways. There is a very fast cessation of

α-motoneuron activity to the mandibular closing muscles brought about by a sudden unloading of the muscle spindles due to the sudden mandibular closure. The unloading leads to a sudden decrease in Ia afferent input to the mandibular closing motoneurons. This decreases the activity of the mandibular closing motoneurons and thereby decreases activity in the motor units of the mandibular closing muscles. At the same time, a jaw-opening reflex is activated as described above where the mandibular openers are briefly activated and the mandibular closers are briefly further inhibited to help to prevent further mandibular closing. Furthermore there are likely other physical properties of the masticatory system such as viscoelasticity (damping) of the soft tissues and the individual's intent that contributes to limiting damage to events such as sudden unloading of the mandible (Johansson et al. 2014; Peck et al. 2002).

#### Role of Reflex Pathways in Mandibular Posture

We can also sense the rapid downward force applied to the mandible as the front foot hits the ground in running. The fast feedback of afferent information from the muscle spindles to the α-motoneurons of the mandibular closing muscles results in a brief contraction that minimizes the opening of the mandible that prevents the mandible flopping up and down when you are walking and running.

As mentioned above, muscle spindles are very sensitive and appear to play a role in the maintenance of the mandibular rest position or postural position. Some authors have proposed that the postural position is maintained only by the passive viscoelastic forces of the tissues supporting the mandible. While there is little evidence for muscle activity in the masseter muscles when the mandible is in the postural position, recent data have demonstrated tonic activity in the medial pterygoid and temporalis muscles while the mandible is in the postural position (Yilmaz et al. 2015; Chen, Mojaver, Whittle, Klineberg, Murray, unpublished observations). While these initial observations need further confirmation, it appears nonetheless that the rest or postural position of the mandible may be at least partly maintained by activity in some mandibular closing motor units, and these may be located in the medial pterygoid and temporalis muscles. It is likely that this tonic activity arises from the slight stretch of the muscle spindles within the medial pterygoid and temporalis muscles because of the pull of gravity on the mandible. The subsequent Ia afferent discharge then would tonically activate the lowest-threshold (i.e., most easily activated) motor units of these mandibular closing muscles to help maintain mandibular posture (see Fig. 3.9).

### 3.2.2.3 Rhythmical Movements

The generation and control of rhythmical orofacial movements, namely, mastication and swallowing, have been extensively reviewed (Jean 2001; Lund 1991).

Rhythmical movements are movements such as mastication, swallowing, breathing, walking, running, and swimming. They share features of both reflex and voluntary movements. We do not have to think about these movements for them to occur and in that sense they have features of reflexes. However, they also have features of voluntary movements in that we can start and stop rhythmical movements, we can usually make them go faster or slower, or we can exert more effort or less effort. For example, we can chew, breathe, and walk without thinking specifically about the task, and we can at any time stop chewing, breathing, and walking or move faster or slower or exert more force or less force during the movement.

The rhythmical movements associated with mastication are generated and controlled by a group of neurons in the pontomedullary reticular formation of the brainstem. These neurons constitute the CPG for mastication. Figure 3.9 shows some relations of the CPG for mastication in the brainstem. Swallowing is also controlled by a CPG located in the medulla oblongata and is likely associated with neural circuitry that overlaps the neural circuitry for mastication.

A CPG is a neural network (red box labelled CPG in Fig. 3.9) that is like a computer program. When it is activated, the CPG generates action

potentials of the required intensity and timing to the various facial, mandibular, and tongue muscle motoneurons (red outputs from trigeminal, facial, and tongue motor nuclei, Fig. 3.9) so that the associated muscle fibers become activated in the correct sequence and magnitude to allow the rhythmical facial, mandibular, and tongue movements seen in mastication to occur.

We can also voluntarily start and stop chewing as well as change the rate and magnitude and shape of the chewing movements, and these modifications are done through descending commands to the CPG from the motor cortical regions. These descending commands are indicated by the bold red line from the face SI, face MI, and the cortical masticatory area (CMA) regions of the cortex to the CPG (Fig. 3.9). The CMA and parts of the face MI and SI are thought to be responsible for many of the voluntary changes in the chewing cycle that are possible such as voluntarily starting and stopping chewing and voluntarily chewing harder and softer.

A CPG for mastication would be of little use to us if it did not accommodate and be capable of changing its activity in accordance with the nature of the food bolus or even to changes in the occlusion. For example, and as described above (Van der Bilt 2011; Woda et al. 2006), our chewing cycle automatically adjusts to harder foods and softer foods. Also as indicated above, somatosensory feedback is crucial for proper functioning of the masticatory CPG. This feedback is provided by mechanoreceptors such as periodontal mechanoreceptors which signal the magnitude and direction of tooth contact and also mucosal mechanoreceptors which signal food contact with mucosa. In addition, muscle spindles signal muscle length and rate of change of muscle length as the mandible closes, while Golgi tendon organs signal forces generated within muscles, and TMJ mechanoreceptors signal mandibular position and joint loads.

Somatosensory information plays a crucial role in allowing the chewing cycle to modulate so as to accommodate to changes in food bolus consistency (Lund and Olsson 1983). Chewing is associated with a barrage of somatosensory information entering the CNS. Some of this information passes rapidly to the cerebral cortex (e.g., face SI and higher cortical areas, Fig. 3.9) for perception, e.g., perception of a food bolus between the teeth during chewing, and contact between tongue and a food bolus during chewing. Some of the afferent information also passes directly to the CPG (Fig. 3.9; blue arrow from TBSNC to CPG) to allow rapid modulation of the CPG to adjust the chewing cycle timing and amplitude to accommodate to the texture and hardness of the food bolus. Thus, for example, encountering hard foods in the early part of chewing means that chewing needs to start off so that forces are sufficiently high to break through the food bolus. Then, as the food is softened as chewing progresses, the forces need to be reduced rapidly in magnitude so that the teeth do not bang together. This can all be done without thinking about the changes required in the levels of muscle activity during chewing and can be controlled by the CPG aided by somatosensory input from mechanoreceptors in the oral cavity. As indicated above, periodontal mechanoreceptors can play an important role here as they signal the magnitude and direction of forces applied to the teeth, and also muscle spindles play a role (Fig. 3.9; blue arrow-labelled R indicates afferent input, e.g. periodontal, passing to modulate α-motoneuronal activity).

Many of the orofacial afferents that are activated during the mandibular closing phase of chewing can evoke a jaw-opening reflex (see above). If this occurred during chewing, then this would not be useful as closing would be prevented. Lund and Olsson carried out some elegant research in the 1970s and 1980s to show that the masticatory CPG actually depresses the responsiveness of the jaw-opening reflex during the closing phase of the chewing cycle (Lund and Olsson 1983). This means that the normal operation of the jaw-opening reflex is markedly depressed during the closing phase of the chewing cycle. If this did not happen, then we would have difficulty in chewing our food. This effect allows the mandible to close unhindered.

During the opening phase of the chewing cycle, muscle spindles in the mandibular closing muscles will be stretched, and the sensory information from them will have an excitatory effect

on mandibular closing motoneurons. This could lead to activation of mandibular closing muscles with the net effect of resisting mandibular opening. However, during the opening phase of the chewing cycle, the masticatory CPG hyperpolarizes (i.e., inhibits) mandibular closing motoneurons and makes it much harder for them to become activated, and therefore the excitatory input from muscle spindles, which would normally activate the mandibular closing muscles, does not activate during mandibular opening.

The activation of nociceptive afferents during chewing, however, has a profound inhibitory effect on the entire chewing cycle and will immediately stop chewing from occurring. Take, for example, what happens when you bite your cheek during chewing. The activity in nociceptors activates inhibitory connections to the CPG to stop it from cycling.

There is also good evidence for neural changes at higher levels of the CNS in association with changes to the occlusion (Lund and Olsson 1983; Sessle 2016), and these changes are also likely to be operative at the level of the CPG. Thus, it is likely that the CPG can undergo neuroplastic changes to allow it to accommodate to changes in occlusion as would be provided by new dentures, new crown and bridgework, implants, etc.

#### 3.2.2.4 Some Autonomic Aspects

The sympathetic nervous system plays a critical role in normal muscle function and has also been implicated in the mechanisms of muscle pain. These effects have been reviewed (Passatore and Roatta 2007) and are briefly summarized here. Thus, the use of muscles involves not only activation of α-motoneurons to muscle fibers but also a parallel set of commands to sympathetic systems to increase blood flow to the active muscle. The vasoconstrictor action of the sympathetic nervous system is overridden by the powerful vasodilator actions of muscle metabolites. An imbalance between these two forces may lead to ischemia in the working muscles, which together with the buildup of metabolites may activate muscle nociceptive terminals and result in muscle pain, or myalgia.

An interesting effect noted for the sympathetic nervous system control of muscles is that sympathetic activation depresses the sensitivity of muscle spindle afferents to be able to detect length and velocity changes. This effect is thought to be brought about through the sympathetic innervation of muscle spindles so that an increased sympathetic activation results in an impairment in the ability of the muscle spindle to detect length and velocity changes in the muscle. Therefore under stressful conditions, this effect could significantly impair the abilities, described above, of the muscle spindle in correcting for unexpected perturbations in the masticatory cycle, as well as impairing feedback from the muscle spindle to be used for refinement of the masticatory CPG during chewing. Sympathetic stimulation under stress may also have effects on postural maintenance.

As previously noted (Passatore and Roatta 2007), acute states of stress demand sympathetic activation and result in adjustments that help the organism cope with environmental changes. Prolonged stress however impacts negatively on the individual, and in terms of prolonged sympathetic effects on muscles, it may result in impaired motor control such that individuals may adopt suboptimal strategies of muscle activation that may be harmful in the long term and result in muscle pain.

A close relationship has also been noted between masticatory function and cardiac autonomic function (Hasegawa et al. 2009; Koizumi et al. 2011; Nitta et al. 2003). For example, in experimental animal models, chewing during stress exposure can reduce sympathetic hyperactivity and stress-induced arrhythmias (Koizumi et al. 2011).

## 3.3 The Relations Between Pain and Motor Activity

Chapter 6 describes in detail dysfunction of the masticatory muscles and includes a description of pain–motor interactions. In brief, orofacial pain clinical diagnosis and management, and even research, has been dominated by the notion that there is a simple, reflex-like association between pain and muscle activity (Stohler 1999; Svensson and Graven-Nielsen 2001; Travell et al. 1942; van

Dieën et al. 2003) These theories operate at spinal or brainstem levels and do not incorporate input from higher centers. The vicious cycle theory (Travell et al. 1942) proposes a positive interrelationship between pain and the so-called muscle "hyperactivity." Proponents argue that abnormalities in posture, structure (e.g., jaw misalignment, malocclusion), movement, or stress lead to muscle hyperactivity that leads to further abnormalities and a vicious cycle. Many management strategies based on this theory attempt to break this cycle by, e.g., irreversible and often expensive changes to the anatomy (e.g., surgery, tooth adjustments) (Mense et al. 2001; Sessle et al. 1995; Stohler 1999; Travell and Simons 1983; van Dieën et al. 2003). In contrast, the pain adaptation model (Lund 2008) proposes that pain leads to reduced agonist (the driver of an action) and increased antagonist (resists an action) muscle activity that results in slower and smaller movements so as to minimize further injury and therefore aid healing (Lund 2008; Stohler 1999; van Dieën et al. 2003). Management strategies influenced by the pain adaptation model see no need to break a vicious cycle but rather invoke pharmacological and behavioral strategies to reduce pain and minimize movement to allow the masticatory motor system to heal and recover (Fricton and Schiffman 2008).

Accumulating evidence however indicates that neither the vicious cycle theory nor the pain adaptation model provides an adequate explanation of the association between pain and muscle activity (Lund 2008; Murray and Peck 2007; Simmonds et al. 2006; Stohler 1999; Svensson and Graven-Nielsen 2001; van Dieën et al. 2003). Therefore, two recent new models have been proposed to explain how pain modifies muscle activity, the integrated pain adaptation model (Murray and Peck 2007) and a new theory of the motor adaptation to pain (Hodges and Tucker 2011). Essentially both models propose that noxious stimulation at a site results in a redistribution of activity within and between muscles, and both models incorporate changes in higher centers of the brain (e.g., psychosocial aspects) in determining the final nature of the redistributed motor activity.

## 3.4 Summary

This chapter has summarized the normal internal anatomy and functions of the masticatory muscles. A detailed description is provided as to how the brain controls these muscles in voluntary movements, reflex movements, and rhythmical movements. The basic functional unit of muscle, the motor unit, is described in detail in terms of physiological properties and how motor units are arranged within the masticatory muscles. The muscles have a complex internal architecture where subcompartments of the muscles can be selectively activated independently of other regions, and this is thought to contribute to the sophistication with which forces can be applied to the mandible to achieve the finely controlled forces and movements characteristic of chewing, speech, and other orofacial movements. The orofacial area is richly endowed with somatosensory receptors that not only allow us to sense textures, temperatures, and consistencies of food and liquids but also provide continual feedback that is used by the brain motor systems to refine masticatory movements. Nociceptive pathways are also described and how information along these pathways can be modulated depending on environmental influences as well as how these pathways can become sensitized and responsive even to non-noxious (non-painful) stimuli. These effects can contribute to the allodynia and hyperalgesia seen in acute and chronic pain states. The chapter concludes with a brief outline of possible relations between pain and motor activity. One of the aims of this chapter is to highlight the complexity of the masticatory muscles as well as their sensorimotor brain control systems. Advancements in knowledge will no doubt elaborate on the complexity of the muscles and their control systems that clinicians are called upon to treat. It is incumbent on the clinician to be cognizant that the masticatory system is highly complex, that a simple mechanistic approach to chronic pain management is unlikely to be successful, and that a multimodal and multidisciplinary approach is more appropriate.

## References


Apkarian AV, Hashmi JA, Baliki MN. Pain and the brain: specificity and plasticity of the brain in clinical chronic pain. Pain. 2011;152:S49–64.

Avivi-Arber L, Martin RE, Lee J-C, Sessle BJ. Face sensorimotor cortex and its neuroplasticity related to orofacial sensorimotor functions. Arch Oral Biol. 2011;56:1440–65.

Blanksma NG, van Eijden TMGJ. Electromyographic heterogeneity in the human temporalis muscle. J Dent Res. 1990;69:1686–90.

Blanksma NG, van Eijden TMGJ. Electromyographic heterogeneity in the human temporalis and masseter muscles during static biting, open/close excursions, and chewing. J Dent Res. 1995;74:1318–27.

Cairns BE, Ren K, Tambeli CH. Musculoskeletal orofacial pain mechanisms: insights from animal models. In: Sessle BJ, editor. Orofacial pain: recent advances in assessment, management, and understanding of mechanisms. Washington, DC: IASP Press; 2014. p. 351–72.

Capra NF. Mechanisms of oral sensation. Dysphagia. 1995;10:235–47.

Capra NF, Hisley CK, Masri RM. The influence of pain on masseter spindle afferent discharge. Arch Oral Biol. 2007;52:387–90.

Chiang CY, Dostrovsky JO, Iwata K, Sessle BJ. Role of glia in orofacial pain. Neuroscientist. 2011;17:303–20.

Dubner R, Sessle BJ, Storey AT. The neural basis of oral and facial function. New York: Plenum Press; 1978.

Fricton JR, Schiffman E. Management of masticatory myalgia and arthralgia. In: Sessle BJ, Lavigne G, Lund JP, Dubner R, editors. Orofacial pain: from basic science to clinical management. Chicago: Quintessence Publishing Co, Inc; 2008. p. 179–85.

Goldspink G. Cellular and molecular aspects of muscle growth, adaptation and ageing. Gerodontology. 1998;15:35–43.

Greene CS. Managing the care of patients with temporomandibular disorders: a new guideline for care. J Am Dent Assoc. 2010;141:1086–8.

Haggard P, de Boer L. Oral somatosensory awareness. Neurosci Biobehav Rev. 2014;47:469–84.

Hannam AG, McMillan AS. Internal organization in the human jaw muscles. Crit Rev Oral Biol Med. 1994;5:55–89.

Hasegawa Y, Sakagami J, Ono T, Hori K, Zhang M, Maeda Y. Circulatory response and autonomic nervous activity during gum chewing. Eur J Oral Sci. 2009;117(4):470–3.

Hodges PW, Tucker KJ. Moving differently in pain: a new theory to explain the adaptation to pain. Pain. 2011;152:S90–8.

Jean A. Brainstem control of swallowing: neuronal network and cellular mechanisms. Physiol Rev. 2001;81:929–69.

Johansson AS, Pruszynski JA, Edin BE, Westberg K-G. Biting intentions modulate digastric reflex responses to sudden unloading of the jaw. J Neurophysiol. 2014;112:1067–73.

Klineberg IJ, Murray GM. Osseoperception: sensory function and proprioception. Adv Dent Res. 1999;13:120–9.

Koizumi S, Minamisawa S, Sasaguri K, Onozuka M, Sato S, Ono Y. Chewing reduces sympathetic nervous response to stress and prevents poststress arrhythmias in rats. AJP: Heart and Circulatory Physiology. 2011;301(4):H1551–8.

Korfage JAM, Koolstra JH, Langenbach GEJ, van Eijden TMGJ. Fiber-type composition of the human jaw muscles - (Part 1) origin and functional significance of fiber-type diversity. J Dent Res. 2005a;84:774–83.

Korfage JAM, Koolstra JH, Langenbach GEJ, van Eijden TMGJ. Fiber-type composition of the human jaw muscles - (Part 2) Role of hybrid fibers and factors responsible for inter-individual variation. J Dent Res. 2005b;84:784–93.

Lin C. Brain signature of chronic orofacial pain: a systematic review and meta-analysis on neuroimaging research of trigeminal neuropathic pain and temporomandibular joint disorders. PLoS One. 2014;9(4):e94300. doi:10.1371/journal.pone.0094300.

Lund JP. Mastication and its control by the brain stem. Crit Rev Oral Biol Med. 1991;2:33–64.

Lund JP. Persistent pain and motor dysfunction. In: Sessle BJ, Lavigne G, Lund JP, Dubner R, editors. Orofacial pain: from basic science to clinical management. Chicago: Quintessence; 2008. p. 117–24.

Lund JP, Olsson KA. The importance of reflexes and their control during jaw movement. Trends Neurosci. 1983;6:458–63.

Melzack R, Wall PD. Pain mechanisms: a new theory. Science (Washington, DC). 1965;150:971–9.

Mense S, Hoheisel U. Mechanisms of central nervous hyperexcitability due to activation of muscle nociceptors. In: Graven-Nielsen T, Arendt-Nielsen L, Mense S, editors. Fundamentals of musculoskeletal pain. Seattle: IASP Press; 2008. p. 61–73.

Mense S, Simons DG, Russell IJ. Muscle pain: understanding its nature, diagnosis, and treatment. Philadelphia: Lippincott Williams & Wilkins; 2001.

Miller AJ. Craniomandibular muscles: their role in function and form. Boca Raton: CRC Press; 1991.

Murray GM. The lateral pterygoid muscle: function and dysfunction. Semin Orthod. 2012;18:44–50.

Murray GM, Bhutada MK, Peck CC, Phanachet I, Sae-Lee D, Whittle T. The human lateral pterygoid muscle. Arch Oral Biol. 2007;52:377–80.

Murray GM, Peck CC. Orofacial pain and jaw muscle activity: a new model. J Orofac Pain. 2007;21:263–78.

Nitta E, Iwasa Y, Sugita M, Hirono C, Shiba Y. Role of mastication and swallowing in the control of autonomic nervous activity for heart rate in different postures. J Oral Rehabil. 30(12):1209–15.

Palla S, Klineberg IJ. Occlusion and adaptation to change: neuroplasticity and its implications for cognition. In:

Klineberg IJ, Eckert SE, editors. Functional occlusion in restorative dentistry and prosthodontics. Edinburgh: Elsevier Mosby; 2016. p. 43–53.

Passatore M, Roatta S. Modulation operated by the sympathetic nervous system on jaw reflexes and masticatory movement. Arch Oral Biol. 2007;52:343–6.

Peck CC, Sooch AS, Hannam AG. Forces resisting jaw displacement in relaxed humans: a predominantly viscous phenomenon. J Oral Rehabil. 2002;29:151–0.

Phanachet I, Whittle T, Wanigaratne K, Klineberg IJ, Sessle BJ, Murray GM. Functional heterogeneity in the superior head of the human lateral pterygoid. J Dent Res 2003;82:106–111.

Phanachet I, Whittle T, Wanigaratne K, Murray GM. Functional properties of single motor units in inferior head of human lateral pterygoid muscle: task relations and thresholds. J Neurophysiol. 2001;86:2204–18.

Sessle BJ. Mechanisms of oral somatosensory and motor functions and their clinical correlates. J Oral Rehabil. 2006;33:243–61.

Sessle BJ. Central mechanisms of craniofacial musculoskeletal pain: a review. In: Graven-Nielsen T, Arendt-Nielsen L, Mense S, editors. Fundamentals of Musculoskeletal Pain. Seattle: IASP Press; 2008. p. 87–103.

Sessle BJ. Face sensorimotor cortex: its role and neuroplasticity in the control of orofacial movements. Prog Brain Res. 2011a;188:71–82.

Sessle BJ. Peripheral and central mechanisms of orofacial inflammatory pain. Int Rev Neurobiol. 2011b;97:179–206.

Sessle BJ. The biological basis of a functional occlusion: the neural framework. In: Klineberg IJ, Eckert SE, editors. Functional occlusion in restorative dentistry and prosthodontics. St. Louis: Elsevier Mosby; 2016. p. 3–22.

Sessle BJ, Bryant PS, Dionne RA. Temporomandibular disorders and related pain conditions. Seattle: IASP Press; 1995.

Sheppard IM, Markus N. Total time of tooth contacts during mastication. J Prosthet Dent. 1962;12:460–3.

Simmonds MJ, Goubert L, Moseley GL, Verbunt JA. Moving with pain. In: Flor H, Dostrovsky JO, editors. Proceedings of the 11th World Congress on Pain. Seattle: IASP Press; 2006. p. 799–811.

Stohler CS. Craniofacial pain and motor function: pathogenesis, clinical correlates, and implications. Crit Rev Oral Biol Med. 1999;10:504–18.

Svensson P, Graven-Nielsen T. Craniofacial muscle pain: review of mechanisms and clinical manifestations. J Orofac Pain. 2001;15:117–45.

Travell JG, Rinzler S, Herman M. Pain and disability of the shoulder and arm. Treatment by intramuscular infiltration with procaine hydrochloride. J Am Med Assoc. 1942;120:417–22.

Travell JG, Simons DG. Myofascial pain and dysfunction: the trigger point manual. Baltimore: Williams and Wilkins; 1983.

Trulsson M. Force encoding by human periodontal mechanoreceptors during mastication. Arch Oral Biol. 2007;52:357–60.

Trulsson M, Van der Bilt A, Carlsson GE, Gotfredsen K, Larsson P, Müller F, et al. From brain to bridge: masticatory function and dental implants. J Oral Rehabil. 2012;39:858–77.

Türker KS. Reflex control of human jaw muscles. Crit Rev Oral Biol Med. 2002;13:85–104.

Van der Bilt A. Assessment of mastication with implications for oral rehabilitation: a review. J Oral Rehabil. 2011;38:754–80.

van Dieën J, Selen LPJ, Cholewicki J. Trunk muscle activation in low-back pain patients, an analysis of the literature. J Electromyogr Kines. 2003;13:333–51.

van Eijden TMGJ, Turkawski SJJ. Morphology and physiology of masticatory muscle motor units. Crit Rev Oral Biol Med. 2001;12:76–91.

Weijs WA, Kwa SHS. The rabbit masseter: organization and function of a heterogeneous muscle. In: Morimoto T, Matsuya T, Takada K, editors. Brain and oral functions. Amsterdam: Elsevier Science B.V; 1995. p. 11–8.

Woda A, Foster K, Mishellany A, Peyron MA. Adaptation of healthy mastication to factors pertaining to the individual or to the food. Physiol Behav. 2006; 89:28–35.

Yilmaz G, Ugincius P, Sebik O, Türker KS. Tonic activity of the human temporalis muscle at mandibular rest position. Arch Oral Biol. 2015;60:1645–9.