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Appendix A: Functional anatomy, physiology, and neural processes of fingertip movement and touch

A-1 Bones involved in fingertip movement  Here, we will first list the bones involved in fingertip movement, for both arms, from shoulder to fingertip. An overview of these bones is shown in Figure A-1. Attached nearest to the torso, or most proximal, is the humerus [Zygote Media 2012]. This bone lies within the upper arm. The next two bones lying more distal, or further away in their attachment to the torso, are the ulna and the radius. These lie roughly parallel, within the forearm, both having their proximal ends attached to the distal end of the humerus. Near the hand, the distal end of the radius lies on the side of the thumb, while that of the ulna lies on the side of the little finger. Here, both radius and ulna attach to the bones of the wrist, or carpus.

Figure A-1  Bones involved in index fingertip movement. Here, shown for the right hand and arm.

There are eight carpal bones, fitting together within the wrist. Unlike the other bones discussed here, the carpal bones do not have an elongated shape. If the other bones may seem like sticks, the carpal bones will seem more like pebbles. They can be divided into two rows, one lying proximal, one distal [Tubiana et al. 1996]. The
proximal row of carpal bones, from the radial to the ulnar side, consists of the scaphoid, the lunate, the triquetrum, and the pisiform. The distal row of carpal bones, from the radial to the ulnar side, consists of the trapezium, the trapezoid, the capitate, and the hamate [Sobotta et al. 1994].

Beyond the carpal bones are the five metacarpal bones, with their proximal ends attached to the distal row of the carpus. They extend further distally, lying next to eachother across the breadth of the hand. Each metacarpal can be considered the first bone of a separate chain of bones, continuing distally, with each chain corresponding to one of the five digits of the hand. For each chain, the next more distally attached bone is a proximal phalanx. The proximal phalanges lie within the respective segments of the thumb and fingers which are first seen to clearly stick out from the rest of the hand. Before the end of each chain, the fingers have a middle phalanx within their next more distal segment. Such a phalanx is not present in the thumb. Each chain is ended by a distal phalanx, forming the skeletal basis for each fingertip.

A-2 Joint movements causing fingertip movement How the bones listed above are movable relative to eachother determines fingertip movement during instrumental control of musical sound. To indicate specific types of externally observable movement that result from the various articulations, specific anatomical terms can be used. Paired with the names of the joints involved, these terms can then be used to unambiguously indicate main types of movement which may occur. Here, in this way, we will list contributing joint movements, from shoulder to fingertip. A visual overview is given in Figure 1.7.

At the shoulder joint, the humerus is moved relative to the shoulder blade in three types of rotation [Sobotta et al. 1994]. By moving the upper arm, these rotations also move the forearm and hand. For the purpose of describing each rotation, we will assume here that the upper arm initially hangs down along the torso. Then, in shoulder anteversion/retroversion, the humerus rotates forward and backward, respectively, swinging the upper arm forward and backward relative to the torso. In shoulder adduction/abduction, the upper arm is swung sideways relative to the torso: toward it, and away from it, respectively. Finally, in shoulder endorotation/exorotation, the upper arm is rotated around its longitudinal axis, inward toward the front of the torso, or in the opposite, outward direction, respectively. Other movements of the shoulder, such as shrugging, result from displacements of the shoulder blade and clavicle. Such displacements also occur during the three rotations just mentioned [Ten Donkelaar et al. 2007]. However, we will not further discuss these movements here, considering them of, and not relative to, the torso.

At the elbow joint, the ulna and radius together flex and extend relative to the humerus [Sobotta et al. 1994]. This elbow flexion/extension moves the forearm with the hand in a hinge-like motion relative to the upper arm.

Within the forearm, the radius, lying along the ulna, can rotate around it, forming the radioulnar joint. The resulting movement of forearm pronation/supination will turn the entire hand, since it is attached to the radius at the wrist. Rotation in the direction
turning the palm upward is called supination, rotation turning the palm downward, pronation [Sobotta et al. 1994].

In general, the joint movements at the wrist are the combined result of individual articulations involving the various carpal bones, driven by the excursion of muscles originating within the arm [Sobotta et al. 1994]. Our overview of this, here, and also of the more distal joint movements, below, will be based on information scattered throughout [Tubiana et al. 1996], unless indicated otherwise. In *wrist radial/ulnar deviation*, the hand is turned sideways toward either the radius or the ulna. This involves articulations between the carpal bones inside the wrist, as well as between the proximal row of carpal bones and the radius and ulna. The result is an overall joint movement which can rotate the hand across ± 60°. In *wrist palmar/dorsal flexion*, either the palm of the hand or its back (dorsum) is flexed toward both the radius and the ulna. The muscles causing this insert, via tendons, at various locations on and near the proximal ends of the metacarpals. In the resulting flexion of the metacarpals relative to both radius and ulna, the index and middle metacarpals are fixed rigidly to bones inside the distal carpal row, so that these all move together as a single unit. This forms the basis for an overall joint movement rotating the hand across ± 160°.

Other metacarpals however can move independently. On the radial side, the thumb metacarpal can move in multiple ways relative to the carpal bones and the other metacarpals. However, as our focus is on movement of the tips of the fingers, we will not discuss these movements here, only noting that the specific articulations underlying them enable the thumb to become opposed to, and be brought into contact with, any of the fingertips of the same hand. On the other, ulnar side, the little finger metacarpal can be separately flexed, so as to move its palmar side toward the forearm and also rotate it toward the thumb. This movement of *little finger opposition* is based on the contraction of a muscle which originates at the carpus and inserts on the ulnar side of the little finger metacarpal [Ten Donkelaar et al. 2007].

Between the metacarpal bone of each finger and its proximal phalanx lies a metacarpophalangeal (MP) joint. On the outside, the location of the MP joint is visible as the knuckle at the base of the finger (see Figure A-1). On the inside, three tendons and three muscles enter each finger here. This includes two flexor tendons entering on the palmar side, and one extensor tendon entering on the dorsal side. All of these tendons are attached to muscles which lie outside of the hand, within the arm. Also entering the finger, on its radial and on its ulnar side, respectively, are two interosseous muscles, originating between the metacarpal bones of the hand. An exception to this is the little finger, which only has an interosseous muscle entering on its radial side; on the ulnar side, it has the “abductor digiti minimi” muscle instead. Finally, a lumbrical (“worm-like”) muscle also enters on the radial side of each finger. It is exceptional, in that it originates not on a bone, but on a tendon. More precisely, the lumbrical muscle originates on a section, lying within the palm, of one of the two flexor tendons also entering the finger [Ten Donkelaar et al. 2007]. Together, these three muscles and three tendons continue distally into the finger, inserting in various combinations at various locations of its bony and fibrous skeleton. Based on a number of interacting and non-
trivial mechanisms inside the finger, the coordinated contraction of the muscles involved results in another four types of externally observable joint movement.

In MP joint flexion/extension, the proximal phalanx is flexed toward or extended away from the palmar side of the metacarpal. In what, for clarity's sake, we will call MP joint radial/ulnar deviation, the proximal phalanx is turned sideways, within a more limited angular range, flexing toward either the ulna or the radius. (Conventionally, this movement is often called abduction/adduction, and defined as rotation away from or toward the middle finger. However, it seems the movement also exists for the middle finger itself.) The MP joint movements, by moving the proximal phalanx, move the finger as a whole. Continuing more distally, between the proximal phalanx of each finger and its middle phalanx lies a proximal interphalangeal (PIP) joint. Here, in PIP joint flexion/extension, the middle phalanx is flexed toward or extended away from the palmar side of the proximal phalanx, in a hinge-like motion moving the distal part of the finger from the middle phalanx onward. Finally, between the middle phalanx of each finger and its distal phalanx lies a distal interphalangeal (DIP) joint. In DIP joint flexion/extension, the distal phalanx is flexed toward or extended away from the palmar side of the middle phalanx, in a hinge-like motion, moving the fingertip.

A-3 Some general properties of the joint movements causing fingertip movement

So far, our overview of fingertip movement as the result of combined joint movements may seem to suggest a model not unlike that of, say, a segmented robot arm. However, such an impression could easily lead to a number of implicit assumptions which in fact would not be true. To avoid this, we will now highlight some general properties of the joint movements discussed above.

Joint movements often do not produce straight movement trajectories. For example, during MP joint flexion/extension, other rotation than that strictly flexing the proximal phalanx toward the metacarpal is occurring simultaneously. This is due to asymmetries in the components of the bony and fibrous skeleton at the MP joint, as well as other details of the anatomy at this location. Similarly, the rotation during MP joint radial/ulnar deviation is not strictly sideways in the directions indicated, and for similar reasons.

Joint movements often do not happen around fixed axes of rotation. For example, during forearm pronation/supination, when viewed in cross section, the rotation of the radius bone can be described as happening around an axis which lies somewhere inside the ulna bone. However, the ulna itself is simultaneously being rotated, and displaced along a curve, and the location of the main rotational axis will vary during a single movement, as well as between subsequent movements. At the wrist, palmar/dorsal flexion and radial/ulnar deviation, too, are examples of joint movements not restricted to a fixed geometric axis.

Joint movements often are not replicated identically across joints. For example, the proximal phalanges of the fingers have an ulnar inclination in their attachment to the metacarpals. This ulnar inclination varies in amount across the fingers of one hand,
thereby varying the orientation of movements relative to the metacarpal. More generally, although MP joint flexion/extension, MP joint radial/ulnar deviation, PIP joint flexion/extension, and DIP joint flexion/extension are replicated across the fingers, this also includes individual variations in the basic underlying anatomy, resulting in differences between the same movements at different fingers.

*Joint movements often do not happen fully orthogonal to each other.* Different joint movements may very well occur simultaneously, but, due to details of the underlying anatomy, the range of one movement may depend on the current state of another. For example, elbow extension is limited by wrist palmar flexion. Wrist palmar flexion facilitates, however, wrist ulnar deviation; while wrist dorsal flexion facilitates wrist radial deviation. More distally, MP joint flexion limits MP joint radial/ulnar deviation, and during general flexion of the finger joints, the middle and distal phalanges can apply the greatest forces if there is dorsal flexion and ulnar deviation at the wrist.

Lack of orthogonality may also mean that movements become mirrored across joints. For example, some of the extensor tendons combining to enter at the finger MP joints are attached to each other across the back of the hand; while some of the flexor tendons of the middle, ring and little fingers attach to the same muscle. As a result of such underlying anatomy, movement at the joints of one finger may often induce simultaneous movement, in a similar direction, in adjacent fingers. Perhaps the strongest example of mirroring, however, are PIP and DIP joint flexion/extension near the fingertip. At least partly due to the anatomy of the fibrous skeleton at these joints [Ten Donkelaar et al. 2007], PIP and DIP joint flexion/extension typically happen simultaneously and in the same direction.

**A-4 Somatosensory receptors for fingertip movement** Distributed across various anatomical areas, there exist various types of somatosensory receptors that are essential to normal human fingertip movement. We will discuss these below, with Table 1.8 providing a summary.

*Muscle spindles* are located within the muscles and transduce muscle length, as well as the speed of muscle length changes. Here, the somatosensory neuron is attached to a spindle made of 3 to 10 thin muscle fibers that stretch along and respond when the nearby ordinary muscle fibers are stretched. During contraction of the ordinary muscle fibers, specialized motor neurons contract the spindle fibers too, ensuring that they keep stretching along with the ordinary muscle fibers. The action potential characteristics of different types of muscle spindles together transmit the properties just mentioned [Wolters and Groenewegen 2004].

*Golgi tendon organs* are located between a tendon and the muscle it attaches to, and transduce muscle tension and changes in muscle tension. They adapt slowly, and may respond when muscle spindles do not, in cases where changes in muscle tension do not produce changes in muscle excursion. On the other hand, a relaxed muscle that is being stretched may change in length while not changing the tension it applies, resulting in muscle spindles that respond while the Golgi tendon organs do not [Wolters and
There are receptors much like Golgi tendon organs present in tissues within and around the joints, transducing events related to joint movement.

**Ruffini mechanoreceptors** are located in tissues within and around the joints, and also deeper in the skin below the epidermis. They transduce mechanical deformation, and mechanical vibration. They respond best to vibration waves with frequencies in the 15-400 Hz range [Goldstein 2002]. In the skin, they adapt slowly, and their sensory units have relatively large receptive fields. There, they are often called slowly adapting type 2 (SA2) cutaneous receptors [Goldstein 2002]. In the joints, however, Ruffini mechanoreceptors adapt rapidly [Wolters and Groenewegen 2004].

**Vater-Pacini mechanoreceptors** are located in tissues within and around the joints; deeper within the skin below the epidermis; at the surface of tendons and fascia (fibrous connective tissues, e.g. around muscles); in the walls of blood vessels; and in the periosteum (an outer membrane of bones, for long bones absent at the joints) [Kahle 2001] [Wolters and Groenewegen 2004]. They transduce changes in mechanical deformation, and mechanical vibration. Vater-Pacini mechanoreceptors respond best to vibration waves with frequencies in the 10-500 Hz range [Goldstein 2002]. Within the skin, they adapt rapidly, and their sensory units have relatively large receptive fields. Here, they are often called rapidly adapting type 2 (RA2) cutaneous receptors [Goldstein 2002]. In the joints, however, Vater-Pacini mechanoreceptors adapt slowly [Wolters and Groenewegen 2004].

**Merkel (SA1) mechanoreceptors** are located within the skin near the boundary between epidermis and dermis. They transduce mechanical deformation, and low-frequency mechanical vibration. Merkel (SA1) mechanoreceptors respond best to vibration waves with frequencies in the 0.3-3 Hz range [Goldstein 2002]. Adapting slowly, and with their sensory units having relatively small receptive fields, they are often called slowly adapting type 1 (SA1) cutaneous receptors [Goldstein 2002].

**Meissner (RA1) mechanoreceptors** are also located within the skin near the boundary between epidermis and dermis. They transduce (light) mechanical deformation, and low-frequency mechanical vibration. Meissner (RA1) mechanoreceptors respond best to vibration waves with frequencies in the 3-40 Hz range [Goldstein 2002]. Adapting rapidly, and with their sensory units having relatively small receptive fields, they are often called rapidly adapting type 1 (RA1) cutaneous receptors [Goldstein 2002].

**Nociceptors** are located throughout the skin, and throughout various other tissues of the hand and arm. They transduce mechanical, thermal and chemical events associated with the occurrence of tissue damage [Wolters and Groenewegen 2004] [Carlson 1998]. Nociceptors adapt slowly, and in most cases are presumed to be free nerve endings [Wolters and Groenewegen 2004].

**Thermoreceptors** are located within the skin, and transduce changes in temperature. They are widely considered to be types of free nerve endings which increase their firing rates on changes in temperature as small as 0.2 °C, but rapidly adapt to more
constant temperature levels [Wolters and Groenewegen 2004]. Upward and downward changes in temperature are transduced by different types of thermoreceptors. Receptors for cooling respond in the 20-45 °C range, and best around 30 °C. Receptors for warming respond in the 30-48 °C range, and best around 44 °C. (The internal body temperature of a human typically is around 37 °C) [Goldstein 2002]. Warmth receptors lie deeper in the tissue of the skin than cold receptors [Carlson 1998].

So far, we have not discussed Krause receptors [Kahle 2001] or Golgi-Mazzoni receptors [Tubiana et al. 1996]. This has been due to problems in obtaining clear information on the separate nature of these related receptor types. Also, we have not discussed cutaneous somatosensory receptors that are specific to hairy skin, since the skin surrounding the fingertip is glabrous.

A-5 Types of passive touch and their underlying somatosensory transduction

Here, we will list a number of roughly indicated types of passive touch, and discuss for each case which of the types of somatosensory receptor discussed in Section A-4 are assumed [Kahle 2001] to cause sensation via transduction.

First, there exist various skin pressure sensations. Sensations of pressure being applied, or released, may involve the Vater-Pacini (RA2) mechanoreceptors [Goldstein 2002]. Sensations of slowly being pushed against, being lightly tapped, and detailed pressure changes over time (such as those of raised-dot patterns moving across the skin) may involve the Merkel (SA1) mechanoreceptors. Meissner (RA1) mechanoreceptors are also involved in (light) skin pressure sensations. A measure of the size and density of the receptive fields underlying these sensations is the two-point threshold: the smallest distance between two needles placed on the skin for which they are still perceived separately. Across the human body, the two-point threshold is lowest at the fingertips, where it is ± 2 mm. For comparison, the two-point threshold is ± 4 mm at more proximal parts of the finger, and ± 8 mm at the palm [Wolters and Groenewegen 2004].

The Ruffini (SA2) mechanoreceptors are involved in various skin stretch sensations [Goldstein 2002].

Furthermore, the Ruffini (SA2), Vater-Pacini (RA2), Merkel (SA1) and Meissner (RA1) mechanoreceptors may be involved in various skin vibration sensations, based on the overlapping frequency ranges describing their sensitivity to mechanical waves (see Table 1.8). Given the presence of Ruffini and Vater-Pacini mechanoreceptors in tissues within and around the joints, and the additional presence of Vater-Pacini mechanoreceptors at the surface of the tendons and fascia, in the walls of blood vessels, and in the periosteum, it seems appropriate to mention the possibility of vibration sensations originating from other tissues involved in fingertip movement, too.

The proprioceptive sensations are defined as those which convey a sense of position of the limbs [Goldstein 2002]. Such sensations may be based on transduction of muscle length by the muscle spindles [Wolters and Groenewegen 2004], but may also involve
the skin mechanoreceptors, e.g. as when the dorsal skin of the hand becomes stretched due to finger flexion [Tubiana et al. 1996].

The *kinesthetic sensations* are defined as those which convey a sense of movement of the limbs [Goldstein 2002]. As the fingertip is being moved passively, sensations of the presence, speed and direction of its movement may involve muscle spindles within the muscles [Wolters and Groenewegen 2004], Golgi tendon organs between the muscles and tendons [Carlson 1998], and within and around the joints, the receptors similar to Golgi tendon organs, as well as Ruffini and Vater-Pacini mechanoreceptors [Wolters and Groenewegen 2004].

Transduction by the nociceptors of various mechanical, thermal, chemical and electrical events associated with the infliction of tissue damage may result in unpleasant *pain sensations* [Carlson 1998] [Kahle 2001] [Wolters and Groenewegen 2004].

Finally, various *temperature sensations* may result from transduction by the warmth and cold thermoreceptors within the skin. Typically, sensations of warmth and cold indicate changes in skin temperature, and soon become replaced by a sense of neutrality when no further changes are detected. The same temperature may then be experienced at once as both warm and cold at different skin sites, if these previously have adapted to different temperature levels. However, at the boundaries of the temperature ranges transduced by the thermoreceptors, the nature of temperature sensations shifts from relative to absolute [Carlson 1998].