Anatomic basis for individuated surface EMG and homogeneous electrostimulation with neuroprostheses of the Extensor Digitorum Communis

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Running head: Individuated EMG and electrostimulation in EDC

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**Abstract**

The Extensor Digitorum Communis (ED) is generally regarded as a fairly undiversified muscle that gives extensor tendons to all fingers. Some fine wire EMG investigations have been carried out to study individuation of the muscle parts to the different fingers. However, individuated surface EMG of the ED has not been investigated. This study analyses the anatomy of the ED muscle parts to the different fingers in detail, and proposes optimal locations for surface or indwelling electrodes for individuated EMG and for electrostimulation with neuroprostheses. The dissections show that the ED arises from extensive origin tendons (OT) which originate at the lateral epicondyle and reach far in the forearm. The ED OT is V-shaped, with shorter central tendon fibers, but with a long radial and an even longer ulnar slip. The ED parts to the individual fingers consistently arise from distinct OT locations: the ED3 (medius) arises proximally, the ED2 (index) from the radial slip distal to ED3, the ED4 (ring finger) from the ulnar slip distal to ED3, and the ED5 (to ring/little finger) from the ulnar slip distal to ED4. This lengthwise widely spaced arrangement of ED parts compensates to some degree for the narrow ED width and suggests that ED parts should be individually assessable by indwelling and even by surface EMG electrodes, albeit in the latter case with variable mutual crosstalk. Conversely, the anatomic spacing of ED parts warrants that electromyographic stimulation with neuroprostheses by a single implanted electrode cannot likely homogeneously activate all ED parts.

**Keywords**

Anatomy, hand, extensor digitorum communis, electromyography, electrostimulation, function restoration, quadriplegia
# Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>APL</td>
<td>abductor pollicis longus</td>
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<tr>
<td>ECRB</td>
<td>extensor carpi radialis brevis</td>
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<tr>
<td>ECRL</td>
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<tr>
<td>ECU</td>
<td>extensor carpi ulnaris</td>
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<td>extensor digitorum communis</td>
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<tr>
<td>ED2..ED5</td>
<td>muscle parts of ED to index, medius, ring and to common tendon to ring and little finger</td>
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<td>extensor digiti minimi</td>
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<td>extensor indicis</td>
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<tr>
<td>EMG</td>
<td>electromyography</td>
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<td>EPB</td>
<td>extensor pollicis brevis</td>
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<td>EPL</td>
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<tr>
<td>ET</td>
<td>end tendon</td>
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<tr>
<td>HRJ</td>
<td>humerus-radius joint</td>
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<tr>
<td>RLJ</td>
<td>radius-lunate joint</td>
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<tr>
<td>RL</td>
<td>radius length</td>
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<td>OT</td>
<td>origin tendon, origin tendon sheet</td>
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Introduction

The Extensor Digitorum Communis (ED) is generally described as a common muscle from which four or more tendons emerge to the fingers. Dorsal at the hand these tendons are connected by intertendinous connections, known as juncturae intertendinei (Fig. 1). The juncturae are variable in width and direction, ranging from slight to almost fusions of the extensor tendons into a tendon sheet. By direct mechanical action, the juncturae may severely limit independent extensor tendon movement, which may, for instance, affect playing movements in musicians (Leijnse et al. 1992; Leijnse et al. 1993). Being superficial, the juncturae have been described many times (el-Badawi et al. 1995; Hirai et al. 2001; Kitano et al. 1996; Seradge et al. 1999; von Schroeder and Botte 2001; 1995; 1993; von Schroeder et al. 1990; Wehbe 1992; Zilber and Oberlin 2004). Far less attention has been given to the structure of the ED muscle body in the forearm. Commonly it is assumed that because of the tendon displacement limitations from the juncturae, the independence of ED parts to the different fingers is also limited. Anatomically, this is emphasized by the fact that the index and little finger have an extra, independent extensor muscle - the extensor indicis (EI) and extensor digiti minimi (EDM), respectively. However, also in the middle and ring fingers more or less independent finger extension is possible, so that some independence must exist in the corresponding ED muscle parts.

In functional assessment, ED needle electrode studies (Keen and Fuglevand 2004) and detailed needle electrode studies on human and primate finger flexors, extensors and intrinsics (Reilly and Schieber 2003; Schieber 1995; Schieber et al. 2001) were conducted, as well as crosstalk analyses of forearm muscles (Mogk and Keir 2003). Surface EMG of individuated activity of ED parts to the fingers has to our knowledge
not been explored. Clinically, in upper limb paralysis, it is attempted to restore gross hand function by neuroprostheses through muscle stimulation by surgically implanted electrodes (Carroll et al. 2000; Hausman and Masters 2002; Hobby et al. 2001; Taylor et al. 2002). In such treatment, optimal anatomic electrode positioning is of prime importance.

The aim of this study was to determine (i) the anatomic basis for individuated ED finger extension, (ii) the feasibility and optimal electrode locations for individuated ED surface EMG, and (iii) optimal neuroprostheses finger extensor electrode locations for hand opening in grasp.

Morphologically, a consistent gross individuation of the ED parts to index, middle and ring fingers was found, correlating with distinct locations at the ED origin tendons. Concepts on the relationship between origin tendons and muscle morphology were presented in (Leijnse 1997) and are summarized in the methods to facilitate the anatomical description.

*Figure 1 here*
Materials and methods

Concepts - origin tendons, bipennate origin tendons, fascias

The further anatomic descriptions may benefit from the following model of muscle origin tendons (OT). As a model basis for gross description, it is assumed that muscles are assemblies of parallel elementary units, consisting of an individual tendon fiber, a muscle fiber and a tendon fiber in series, spanning between bone attachments. The individual tendon fibers of the individual muscle fibers assemble in tendon fiber sheets, one of origin, one of insertion (Fig. 2.a). The tendon sheets lose thickness or gain thickness as tendon fibers terminate by giving rise to their muscle fibers, or are added as muscle fibers insert with their tendon fibers (Fig. 2.a). The OT sheets, while themselves arising from small areas or lines on bone, vastly expand the skeletal surface area for muscle attachment and allow muscles, such as the extensor digitorum and other forearm muscles, to develop their muscle bodies far from the actual OT bone attachment (Leijnse 1997).

Bipennate OT sheets or intermuscular septa. It is common in the extremities to find adjacent muscles arising from both sides of the same OT sheet, which is then anatomically also called an ‘intermuscular septum’. In the above model, such bipennate OT consists of the fusion of two unipennate OT sheets of two muscles stacked back to back (Fig. 2.b). This model agrees with the fact that bipennate OT sheets may split in their distal course in two unipennate OT slips, which continue as separate OT for the individual muscles (Fig. 2.b).

Fascias. OT sheets must be contrasted with fascias. Fascias are here defined as sheets of connective tissue separating muscles in compartments, without containing tendon fibers of muscle origin or insertion. However, tendon fibers of muscle origin can be embedded in, or covered by fasciatic tissues, which may continue as true fascias after all tendon fibers have ended in muscle fibers (Fig. 2.a).
concepts are of relevance in anatomical ED description. For instance, the posterior fascia antebrachii that covers the ED in the forearm is distally a true fascia (containing no tendon fibers of muscle origin), but proximally contains a deep layer of OT fibers covered by fascia tissue.

Figure 2 here

Specimens

Fifteen forearms of lightly embalmed bodies were amputated 10 cm proximal to the elbow. Light embalming preserves refrigerated specimens for about three weeks while not significantly affecting tendon tissue stiffness (Anderson 2006), allowing detailed and realistic observations. In the first five specimens, the extensor muscles were qualitatively dissected and photographed in detail (Nikon D100 camera with Nikon 60mm lens, bilateral illumination by custom-built fluorescent lights, standard black background, scale in view). When it became clear that the muscle parts of the ED had a constant individuated morphology, the ED and all extensor muscles of the forearm in ten additional specimens were quantitatively documented (Table 1).

Dissection procedures

Skin was removed and the posterior fascia antebrachii cleaned from fat. The outline of the extensor muscles through the opaque fascia antebrachii was photographed in 5 specimens. In 10 other specimens the surface width of the documented muscles was measured (Table 1). The fascia antebrachii was removed up to the distal edge of the superficial OT sheets of the superficial muscles. The superficial borders of the ED parts to index (ED2) and ring finger (ED4) were identified and their width was measured. The ED2, ED3 and ED4 muscle parts were gently eased apart, from distal to proximal, without cutting muscle fibers. To facilitate this, the superficial ED OT sheet was incised parallel to the tendon fibers up to the lateral epicondyle. The ED5 end tendon(s) (ET) were identified and its muscle body dissected from ED4 from
distal to proximal. Thereafter, all other superficial muscles (EDM, ECRB, ECRL, ECU) were measured. Their ET were severed for full access to the deep extensors (EI, EPL, APL/APB), which were similarly photographed or measured. In selected specimens, the neurovascularization was dissected and photographed in detail.

**Measurements**

All measurements were performed by a 200mm range calipers. *Normalization.*

Radius length was measured between the humerus-radius joint (HRJ) and the distal radius edge at the radius-lunate joint (RLJ). The maximum width of radius-ulna at the wrist was measured (Table 1). *Location and length of origins and muscle bodies* (Fig. 3). For each muscle, three length measurements were taken, relative to the HRJ as marked by a pin. (i) The length between the HRJ and the proximal origin edge; (ii) between the HRJ and the distal origin edge, and (iii) between the HRJ and the distal insertion edge of the muscle belly in the end tendon. The latter was measured with the end tendons pulled taut and fingers and wrist in neutral position of extension (which was not always possible, as some finger joints were rigid). If a distance exceeded calipers length (200mm), it was measured relative to the RLJ (marked by a pin) and recalculated relative to the HRJ using the radius length. *Surface widths.* The surface width of the ED, EDM, ECRB, ECRL and ECU was measured with the fascia antebrachii intact. With the fascia removed, but before any dissection, the border between ED2 and ED4 can be identified by a longitudinal line of areolar tissue (Fig. 4.B). ED2 and ED4 surface widths were measured where the proximal edge of the APL crosses the radial edge of the ED (Fig. 4.C) (as will be shown, this site is the proposed optimal anatomic location for ED2 and ED4 surface electrodes). After separating ED2 and ED4 from ED3, the surface width of ED3 was measured.

*Figs. 3 and 4 here*
RESULTS

1. Quantitative anatomy of finger and wrist extensors

(Quantitative data: Tables 1, 2 and Fig. 9)

Superficial finger extensors (ED and EDM)

The V-shaped ED OT compartment. The ECRB, ED, EDM and ECU originate from an extensive complex of OT sheets, which arises from the lateral epicondyle and extends posterior to the ulna. At the epicondyle, the OT sheets arise as a thick tendon band, which unfolds immediately to form distinct OT compartments. Central is the ED compartment, which is proximally cone shaped with relatively short superficial and deep tendon fibers, superficially shorter radial than ulnar. However, the radial and ulnar sides of the ED OT compartment continue distal far into the forearm, giving the ED OT a narrow V-shape with long legs (Fig. 5.C). The radial ED OT reaches to about mid-forearm (49±7 % of radius length RL). The ulnar ED OT reaches up to or beyond the distal third of the forearm (65±9 % RL).

Figure 5 here

Lay-out of the ED parts. Cleaned of fat, the thick posterior fascia antebrachii is opaque and allows identifying the underlying muscle compartments (Fig. 4. A). The fascia can be easily removed up to the distal edge of the superficial ED OT (Fig. 4.B). There the fascia seems to adhere to the muscle, but is in fact connected through the deep layer of OT fibers from which the superficial ED muscle fibers arise. After removal of the fascia up to the OT, the ED muscle body presents as a unit with, however, a thin midline of areolar tissue (Fig. 4.B), which marks the border of ED2 (index) with ED4/ED5 (ring and little finger ED parts). The ED2 and ED4/5 parts can be readily separated from distal to proximal (Fig. 4.C), which exposes the end
tendon and more proximal the muscle belly of the ED3, deep and central in the ED (Fig. 4.D). The ED2 and ED4 can be eased apart from the ED3 up to the OT, the ED2 usually somewhat more easily than the ED4. Obstacles in this separation may occur in the form of small vessels or nerves that cross from one muscle belly to the other. The ED layout thus exposed, found constant in all specimens, is illustrated by Figs. 5.A-D.

- The ED3 origin completely occupies the proximal tip of the ED OT compartment (Figs. 5.A-C). The most proximal ED3 muscle fibers arise well proximal to the HRJ by an average 9.2±3.4 mm or 4.0±1.5 % RL. Distally, the origin area of the ED3 is delimited by the origins of ED2 and ED4. The distal ED3 origin edge and the proximal ED2 and ED4 origin edges may to some degree overlap, as can be seen in Fig. 5.A and C. The total ED3 origin reaches 22.6±5.2 % RL (maximum of edges on radial and ulnar ED OT), slightly more distal radial than ulnar (19.1±5.4 versus 17.8±7.7 % RL, resp.), as is the case in Figs 5.A and B. From these origins, the ED3 muscle belly runs deep to the ED2 and ED4 muscle bellies, reaching to 47.3±5.5 % RL.

- The ED2 origin occupies the radial ED OT distal to the ED3, with the proximal muscle fibers arising at 14.5±4.4 % RL. The proximal ED2 origin at the OT is to some degree superficial to and overlaps to a variable degree with the distal ED3 origin (Fig. 5.A). The most distal ED2 muscle fibers arise at 49.4±7.3 % RL. The muscle belly reaches 74.9±7.9 % RL. The ED2 tendon runs ulnar to the ED2 muscle body near the ED midline (as in Fig. 3).

- ED4 arises from the ulnar ED OT distal to ED3 at 13.7±8.3 % RL, somewhat proximal but with greater variability than the ED2. The ED4 origin reaches 38.8±5.5 % RL, the muscle belly 64.4±6.2 % RL. The proximal ED4 origin may interdigitate with the distal ED3 origin, resulting in a three dimensional interface that may prevent neat separation of these muscle parts near the OT. The ED4 OT envelops the ulnar side of the distal ED3 muscle body so that the ED4 muscle body covers the
distal ED3 muscle belly ulnarly. The ED4 tendon runs central in the ED, adjacent and ulnar to the ED2 tendon. In the mid forearm the ED4 and ED2 muscle bellies are superficially adjacent, entirely covering the ED3 muscle belly and tendon.

- ED5. The ED has an additional muscle part further called ED5. Its ET runs ulnar to the ED4 ET, typically inserts with a V shape in both the ring and little finger, and may practically be considered common to both fingers (Figs. 1). The ED5 ET may be strongly connected to, or even fused with the ED4 ET at the dorsum of the hand (Fig.1.B), but in any case gives a strong junctura to the little finger. The ED5 ET may consist of two or even more tendon strands (Figs. 1.A, D) which at the dorsum of the hand may be strongly interconnected but proximal to the wrist may be individuated from their connective tissues and followed up proximal to sub-layers in the ED5 muscle belly. Occasionally, the ED5 and ED4 muscle bellies can be readily separated pointing to some independent action (specimen in Fig. 5.A, C, D, and Fig. 6.A, and specimen in Fig 6.D). In other cases, the ED4 and ED5 muscle bellies are strongly interconnected by connective tissue, suggesting common action (Specimens in Figs. 6.B, C). The ED5 origin starts proximal at 37.8±5.9 % RL and reaches to 65.4±9.1 % RL, which coincides with the distal edge of the ulnar ED OT. The muscle belly reaches to 85.3±8.8 % RL.

Accessory muscle bellies. The above gross ED outline was found constant in all specimens. However, at the interface of the ED muscle parts small muscle parts may be found arising from the origin area of one part while inserting in another ET. Such ‘cross-overs’ may consist of only a few muscle fibers; the largest found are shown in Figs. 6.C, D, and inserted by their own small tendons in their main end tendon. Cross-overs were found between ED2 and ED3 and between ED3 and ED4, but in our (limited) sample not between ED2 and ED4. Cross-overs are typically distally independent from the muscle mass from which they arise, as they distally move with the end tendon in which they insert.
Extensor digiti minimi. (Figs. 6, A-D) The slender EDM arose in all cases from within its own OT compartment, sandwiched superficially between the ED and ECU. The ulnar EDM compartment side is the radial surface of the radial ECU OT. The radial EDM compartment side is the bipennate ulnar ED OT from which on the radial side the ED4 and ED5 arise, and on the ulnar side the EDM muscle fibers (Fig. 5.D). From these OT the EDM muscle fibers converge to a central tendon. The EDM OT compartment develops proximally at 14.7±5.3 % RL. The origin from the radial ECU OT was generally much shorter than from the ulnar ED OT, reaching to 31.6±2.2% RL as compared to 63.2±9.2 % RL for the latter (Figs. 6.B, D). Distally, the bipennate ulnar ED OT sheet occasionally separated in two individual unipennate OT slips for the ED5 and EDM, respectively, as modeled in Fig. 2.b and shown in Fig. 6.A. Figs. 7 shows the ulnar ED OT after removal of all ED4, ED5 and EDM muscle fibers. The EDM origin reached distally to 63.9±9.2 % RL and the muscle belly to 85.4±6.0% RL.

Widths of ED muscle parts. Table 2, last column, shows that at the surface, ED3 width is greatest at 15.7±4.3mm, ED4 is 11.4±0.8 mm, ED2 is 9.4±2.0 mm and EDM is 9.0±2.1mm, just wide enough for well-placed 4mm cup surface electrodes.

Wrist extensors

Extensor carpi radialis longus. The ECRL arises from short OT fibers from the lateral humerus crest at the lateral epidondyle, starting at 59±11.0 mm or 25.4±4.0 % RL proximal to the HRJ. The ECRL origin continues for a short length of 10.5±9.6 mm or
4.5±3.9 % RL distal to the HRJ at the OT sheet of the ECRB, distally delimited by the origin of the ECRB. The ECRL muscle belly reaches 34.8±3.8 % RL.

*Extensor carpi radialis brevis.* The ECRB arises radial to the ED from within a large half open OT compartment, bluntly 'L'-shaped in transverse cross-section. The ulnar wall of the compartment is the radial ED OT sheet, which is bipennate with the ED arising ulnarly and the ECRB radially. This OT sheet has a large deep unipennate radial expansion which forms the floor of the L shaped ECRB compartment (Fig. 7.A). The most proximal muscle fibers of the ECRB arise 4.2±7.0 mm or 1.7±3.0 % RL distal to the HRJ. The origin reaches to 44.5±3.4 % RL and muscle belly to 67.2±5.5 % RL.

*Extensor carpi ulnaris.* The ECU arises in a closed flat OT compartment that originates at the lateral epicondyle. The most proximal ECU muscle fibers start at 4.0±6.2 mm or 2.4±1.6 % RL. Proximally, the radial (deep) side of the ECU OT compartment is common with the ulnar ED OT, until separated by the EDM compartment. The ECU OT compartment is asymmetric, being much longer radial than ulnar (Fig. 8). The radial ECU OT reaches 71.2±4.0 % RL with its muscle fibers inserting at the radial side of the ECU ET up to 88.5±2.7 % RL. The ulnar (superficial) ECU OT, covered by the posterior fascia antebrachii, reaches barely halfway the forearm at 49.5±4.1 % RL, with its muscle fibers inserting at the ulnar side of the ECU ET up to 67.3±2.1 % RL. More distally the superficial ECU ET surface is bare of muscle fibers, as modeled in Fig. 8 and illustrated in Fig. 4.C, D.
Deep finger extensors

The extensors indicis, pollicis longus and brevis, and the abductor pollicis longus form a deep muscle layer, distal to the supinator (Fig. 7.A, B).

Extensor indicis. The EI arises from the radial surface of the ulna, as well as from short OT fibers from the dorsal ulnar crest and from OT fibers in the interosseus membrane. The EI origin starts proximal at 48.7±3.7 % and reaches 77.0±2.8 % RL. The EI muscle body reaches the most distal of all extensors to 95.5±3.2 % RL, up to or underneath the extensor retinaculum of the wrist (Fig. 7.A, B). Anatomical variations in the EI are not rare - in 3 of 10 arms (2 bilateral in the same subject) accessory muscle bellies/tendons were found. The bilateral accessory tendons inserted ulnar to the ED3 tendon in the extensor assembly of the medius, a variation also described by (von Schroeder and Botte 1991). In the other specimen the accessory tendon was continuous with the thickened distal-radial edge of the sheath enveloping the EI-EPL tendons at the hand dorsum.

Extensor pollicis longus. The EPL arises adjacent, proximal and radial to the EI from the radial surface of the ulna, short OT fibers from the dorsal ulnar crest (Fig. 7.B) and from OT fibers in the membrana interossea. The EPL crosses deep to the ED tendons in a radial-distal course and becomes superficial at entering the third extensor compartment at the distal radius. The EPL ET curves at the ulnar side around the tubercle of Lister and runs then distal-radially to the thumb extension side. The EPL origin starts at 31.0±5.1 % and reaches to 73.0±2.6 % RL. The muscle belly reaches slightly less distal than the EI at 91.6±2.4 % RL.

Extensor pollicis brevis and abductor pollicis longus. The EPB and APL origins (which we consider together) occupy the entire space between the supinator and EPL at the membrana interossea and the ulnar surface of the radius; include OT fibers from radius and ulna, and reach proximal near the ulna even somewhat underneath the
supinator. The APL/EPB origin starts at 24.4±2.1 % RL and reaches to 73.5±5.4 % RL, while the muscle bellies reach 92.5±2.3 % RL.

**Neurovascularization**

The motor branch of the radial nerve emerges distal from beneath the supinator together with the posterior interosseus artery to form a neurovascular plexus of forward and recurrent branches innervating all ED parts, EDM, ECU, APL, APB, EPL and EI (Fig. 10). The ED2-ED5 muscle bellies receive distinct nerve branches entering the ED compartment from deep at the center of the V-shape of the ED OT. Additional vascularization is provided by more distal arteries perforating the interosseus membrane from palmar to dorsal.

*Figs. 9 and 10 here*

### 2. Optimal locations and expected crosstalk with ED surface electrodes

The results show that the muscle bellies of ED2.. ED4/5 are spaced so widely along the forearm that despite their slender build individuated surface EMG should be possible. Surface electrode locations on basis of anatomic proximity are qualitatively derived in Fig. 11 for 4mm cup electrodes drawn on scale and statistically confirmed in Fig. 9. The analysis of expected crosstalk considers as criterion only the anatomic proximity of the neighboring muscles to the electrodes at the targeted muscle.

**ED3.** The ED3 is distally covered by the ED2 and ED4 and inaccessible for surface EMG except near the lateral epicondyle. ED3 Electrodes can be placed as proximal as the HRJ, where they cannot receive significant ED2 and ED4 crosstalk as (statistically) these muscle parts arise distal to the electrodes (Fig. 11.C). The ED4
origin is somewhat more proximal than the ED2 origin, with greater variability. To avoid overlap with very proximal origins of ED4, the ED3 electrodes may be placed somewhat radial (posterior) to the ED midline (Fig. 11.A). Conversely, ED2 and ED4 electrodes placed as in Fig. 11 cannot receive (much) crosstalk from ED3, as at their electrodes the ED3 muscle belly is ending or has already ended. There are no direct deep muscles from which the ED3 electrodes may receive crosstalk, but significant mutual crosstalk exchange can be expected with the adjacent ECRL and ECRB.

**ED2.** ED2 surface electrode locations are determined by three constraints (Fig. 11.A-D). Electrodes must be placed (i) proximal to where the proximal APL edge crosses the radial ED edge, to minimize crosstalk from APL, which is a powerful muscle; (ii) near the distal ED3 muscle belly edge, so that no ED3 activity can be picked up; and (iii) as radial as possible, to avoid crosstalk from the adjacent ED4/5. This determines a narrow range, basically, a single location, at about 45% RL. The ED2 and ED4/5 muscle bellies are adjacent over their entire length, so that mutual crosstalk is unavoidable. Note that, because ED2 is narrower than ED4 (Table 2), ED2 electrodes placed as in Fig. 11 will be closer to ED4 than ED4 electrodes to ED2. ED2 electrodes will thus likely pick up more crosstalk from ED4 than inversely. Minimizing ED4 crosstalk by placing ED2 electrodes at the radial ED2 edge can be envisaged when only ED muscle parts need to be assessed, as in individuated finger tapping tasks with forearm and hand in rest and no wrist extensor activity (Leijnse et al. 2008). With active wrist extensors, radially placed ED2 electrodes will receive increased ECRB crosstalk. From deep, ED2 electrodes may receive APL crosstalk.

**ED4.** The ED4 is surrounded by radially ED2; proximal, radial and deep ED3; and ulnar EDM. ED3 crosstalk is avoided by placing ED4 electrodes near 45% RL, where the ED3 muscle belly is ending. ED2 crosstalk can be minimized by placing the ED4 electrodes near the ulnar ED4 edge, but this increases EDM crosstalk. With a very distal arising EDM compartment, which can sometimes be palpated, ED4 electrodes
may be put somewhat more proximal to minimize EDM crosstalk, but this will increase ED3 crosstalk. With a proximal arising EDM compartment, EDM crosstalk is unavoidable. Crosstalk to ED4 electrodes might also arise from the deep APL/EPB, of which the origins reach ulnarly beneath the ED4 muscle belly (Figure 11.C, D).

**ED5.** The ED5 muscle belly is narrow and anatomically not systematically independent from ED4. Therefore, we do not consider it a candidate for valuable independent surface EMG assessment. ED4 electrodes placed as in Figs. 11 will measure some ED5 activity too.

**EDM.** EDM width is 9.0±2.1 mm, just enough for accurately placed 4mm cup electrodes. EDM electrodes can be placed about halfway up the forearm, which is near the proximal origin edge of the underlying EI. This will minimize EI crosstalk, but EPL crosstalk remains possible. Placing EDM electrodes more distal will increase EI crosstalk. Given the small EDM width, ED4 and ECU crosstalk is unavoidable.

**EI.** The EI muscle belly consistently reaches the most distal of all extensors. EI electrodes may be put as distal and ulnar as just radial to the ulnar head (Fig. 11.D). However, the EDM and ED5 muscle bellies, while reaching on average less distal than EI, are highly variable in length and may reach the EI electrodes (Fig. 9). Such distal EDM and ED5 muscle bellies lay then between EI and its electrodes, so that significant EDM and ED5 crosstalk may result, especially when EI is short, so that its electrodes must be placed more proximally.

**EPL.** The EPL reaches only slightly less distal than EI. The most distal EPL electrode might be placed about 10-15mm proximal to Listers’ tuberculum, at the radial EPL side to minimize EI crosstalk. ED5 crosstalk is statistically to be expected, as the EPL crosses beneath the ED tendons and their distal reaching muscle bellies. As Fig. 11.D shows, some APL/EPB crosstalk can also be expected.

**APL/EPB.** The APL/EPB can be assessed, without great expected crosstalk from any other muscle, radial and lateral-dorsal to the radius at about 75% RL in the forearm.
ECRB. The ECRB tapers considerably at origin and insertion and ECRB electrodes are most isolated from adjacent muscles when placed at the center of the muscle belly, at 40% RL.

ECRL. The ECRL origin reaches proximal on the humerus 59±11.0 mm or 25.4±4.0% RL from the HRJ. ECRL electrodes may thus be placed high on the epicondyle and close to the lateral humerus crest, as far from the ED3 electrodes as possible. Even so, with flexed elbow the ECRL electrodes align closer to the ED3 and may well pick up ED3 crosstalk.

ECU. The ECU is proximally adjacent to powerful muscles: ulnar the anconeus, deep the supinator, and radial the ED. Distal to the anconeus, the radial ECU surface lays against, from deep to superficial, the ulnar-dorsal ulna surface, the ulnar borders of EPL and EI (Fig. 11.D), and the EDM. The thick ECU ET becomes ulnarly free of muscle fibers at 67.3±2.1 % RL, although muscle fibers thin out well proximal to that point (Fig. 8). Therefore, no ECU electrodes should be placed distal to 60% of RL. It follows that, despite the great ECU muscle belly length, optimal ECU electrode locations are actually limited to around 50% of RL, to avoid crosstalk from the large proximal muscles or placing ECU electrodes over the bare distal ET surface.

Figure 11 here

3. Optimal locations for neuroprosthesis finger extensor electrodes

In neuroprosthetic upper extremity palsy restoration, finger extensor electrodes serve to restore hand opening in grasp. Ideally, the fingers are extended evenly, independent of the thumb, allowing thumb opposition/abduction by other means in preparation of subsequent grasping hand closure against an opposed thumb. Optimal neuroprosthesis electrode locations may differ from optimal EMG assessment locations. An EMG signal is after acquisition normalized by maximum voluntary
contraction EMG, meaning that signal strength may be traded for lesser crosstalk by positioning electrodes eccentric at the muscle. In contrast, neuroprosthesis electrodes aim to stimulate a maximum of muscle bulk, requiring electrodes central at the muscle belly. From the dissection data, the following can be proposed.

A single neuroprosthesis electrode cannot likely evenly activate all finger extensors. As shown in Fig. 12, a single electrode at position e1 will activate almost exclusively the ED3 muscle belly, as it does not cover the other ED parts. At position e2 it will strongly activate ED4, but weakly ED2, ED3 and ED5, and almost none of EDM, being strongly eccentric at the latter muscle bellies. At position e3 it will not activate the ED3 muscle belly at all. In conclusion, in all above cases, a single electrode will result in greatly different extension forces in the individual fingers.

A deep single central electrode may indiscriminately activate all finger extensors, including thumb and ECU. A deep electrode near the radial motor nerve plexus (Fig. 10) may activate all extensor muscles except ECRB and ECRL (i.e., ED2-ED5, EDM, EI, ECU, APL, EPB and EPL). Strong thumb extensor activation in hand opening will complicate achieving thumb opposition in preparation of grasp, while the wrist will also ulnarly abduct and extend by the ECU activity.

Three or four electrodes may evenly activate all finger extensors. Three electrodes placed as in Fig. 13, A-C, would cover ED3 (e1), ED2 and partly ED4/5 (e2), and EDM and partly ED4/5 (e3). Four electrodes placed as in Fig. 13, D-F, might provide even more homogenous stimulation, with e1 covering ED3, e2 mainly ED4, e3 covering ED2 and partly ED5, and e4 covering EDM. However, electrode e2 is closer to the RN plexus, although when placed superficial at ED4, it is still shielded from the nerve plexus by the underlying ED3 muscle belly and its ET. Since no individuated finger
extensor function is intended in neuroprosthetic hand opening in grasp, all electrodes can be connected to the same activation channel.

*Fig. 12 and 13 here*
DISCUSSION

*Functional-anatomic extensor digitorum communis individuation*

The ED is generally regarded as a common finger extensor, hence its name. However, the dissection results show that by means of extensive origin tendons, the ED parts to the different fingers are spaced out in a way naturally conducive to individuation. The ED3 arises from the proximal part of the V-shaped OT, ED2 from the radial ED OT, and ED4 and ED5 sequentially from the long ulnar ED OT. No exceptions were found in this pattern in fifteen specimens. While the ED2, ED3 and ED4 were found reasonably well separable, occasionally tendon strands were found crossing between ED2 and ED3, and between ED3 and ED4, but in our specimens not between ED2 and ED4. The ED4 and ED5 could not be consistently separated – such inconsistent individuation can also be observed in their end tendons.

*Individuated EMG assessment in ED and EDM*

The extreme proximal-distal spacing of the ED parts allows placing bipolar surface electrodes in lengthwise spaced locations that partially compensate for the small muscle belly widths. Since all muscle parts are superficial, reproducible individuated EMG should be obtainable at the locations proposed in Fig. 11. Needle electrodes should measure individuated EMG with little crosstalk. With surface electrodes, the expected crosstalk on basis of anatomic muscle part proximity was analyzed in the results. ED3 activity should be measurable without significant crosstalk from or to ED2 and ED4. ED2 and ED4, being adjacent, should be independently measurable but with more mutual crosstalk. ED4 and EDM will have significant mutual crosstalk. Between ED5/EDM and the deep extensors EI/EPL, crosstalk will likely vary with the anatomically variable distal reach of their muscle bellies. Extensor surface EMG assessment in finger tapping tasks closely confirmed the above anatomical
projections (Leijnse et al. 2008). Concerning crosstalk filtering, it has been pointed out that a source of crosstalk is non-propagating waves when action potentials reach muscle fiber ends at their tendon attachment (which happens at OT and ET alike). Crosstalk reductions were proposed by spatial filtering combining outputs of more than two electrodes to accentuate propagating waves from the muscle of interest while attenuating non-propagating waves from other muscles (Farina et al. 2004; van Vugt and van Dijk 2001). In the finger extensors, the application of such techniques or spatial filter choice may not be straightforward. The long OT and ET interlace, so that standing waves will be generated all along the muscle of interest. In closed OT compartments such as ECU and EDM, non-propagating waves will within the same muscle equally arise from muscle fibers inserting at opposite OT tendon surfaces of the compartment, as well as at both surfaces of the bipennate ET. It follows that minimizing crosstalk by electrode placement based on least anatomic proximity remains of prime relevance.

**Optimal ED electrode locations with neuroprostheses**

Usefulness of hand opening in grasp is determined by the fingers with the smallest extension range. Figure 12 suggests that a single electrode cannot likely evenly activate all ED parts and EDM. Therefore, in neuroposthetic hand opening with a single extensor electrode, some fingers will likely trail others. This may result in the need to over-stimulate well simulated ED parts to obtain sufficient stimulation of under-stimulated ED parts to achieve the desired extension range in all fingers. As figs. 13 show, three or four electrodes connected to a single control channel may significantly improve homogenous finger extensor stimulation. The consistent anatomical location of the ED parts and the fact that they can be easily superficially stimulated per-operatively through the fascia antebrachii should allow accurate multiple electrode placement without requiring extensive surgical dissection. A point
of attention remains the radial motor nerve plexus distal to the supinator. An electrode placed near this nerve plexus may unwontedly active all finger and thumb extensors, including ECU, amongst others resulting in compromised thumb opposition with extensor activation in hand opening for grasp.

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Leijnse JN, Campbell-Kyureghyan NH, Spektor D, and Quesada PM. Assessment of individual finger muscle activity in the Extensor Digitorum Communis by surface EMG. *J Neurophysiology (accepted)* 2008.


Legends with the figures

Figure 1
Examples of extensor tendons and juncturae intertendinei. 2-5: index - little finger ED tendons. M: extensor digiti minimi. EI: extensor indicis. Variability ED5 tendons:
A) Duplicated but fused ED5 tendon. B) ED5, ED4 and ED3 tendons fused into a single tendon plate. C) Single ED5 tendon. D) Triple ED5 tendon with one ED5 tendon slip inserting directly in the little finger.

Figure 2
Muscle / tendon models
(a) Unipennate muscle model. OT, ET: origin and end tendon sheets, consisting of the individual OT and ET fibers of the individual muscle fibers. F: fascia, surrounding the muscle and its OT.
(b) Bipennate OT, modeled as two unipennate muscles fused back to back. The OT fibers to the respective muscles may disengage in their distal course (arrow) and continue as independent unipennate OT sheets.

Figure 3
Measured muscle length parameters. L HRJ-PO: length humerus-radius joint (HRJ) to proximal muscle origin edge. L HRJ-DO: length HRJ to distal muscle origin edge. L HRJ-DI: length HRJ to distal muscle insertion edge. L RJI-DI: length distal muscle insertion edge to distal radius edge at radius-lunate joint (RLJ) to. L Radius: radius length, normative measure.

Figure 4
Superficial aspect of extensor digitorum communis (ED)

B. Removal of fascia antebrachii up to OT. In this specimen the superficial ED OT was very long (compare with white arrows in A). White and black arrows: aerolar tissue lines separating ED2 (2) and ED4/5 (4/5), and ED4/5 and EDM, respectively. ECRL, ECRB: extensor carpi radialis longus and brevis, APL: abductor pollicis longus, ECU: extensor carpi ulnaris. LE: lateral epicondyle.

C. Detail of B (rectangle). ED2 and ED4/5, and ED4/5 and EDM separated at the aerolar tissue lines marked in B. Double white arrows: widths of ED2 and ED4/5 where the proximal APL edge crosses the radial ED2 edge; and greatest EDM width (values in Table 2). T2 .. T5: ED2 .. ED5 end tendons. T_{EPL}: extensor pollicis longus ET.

D. Retraction of ED2 and ED4 shows the underlying, independent, short ED3 muscle belly with its long end tendon.

**Figure 5**

Internal ED structure

A. Fully separated ED muscle bellies. ED3 arises from the ED OT compartment central and proximal. ED2 arises distal to ED3 from the radial ED OT. ED4 arises distal to ED3 from the ulnar ED OT, but the proximal ED4 origin overlaps with the distal ED3 origin. ED5 arises distal to ED4 from the ulnar ED OT. ED5 is in this specimen fully independent from ED4.
B. Specimen of Fig. 4.D. ED3 muscle fibers removed, ED2 and ED4 intact, showing the ED3 origin area. PO2 .. PO4: proximal origin edges ED2 .. ED4. PO3 is well proximal to the humerus-radius joint (HRJ), marked by a pin.

C. Specimen of A, ED2-ED5 muscle bellies raised, showing the vast V-shaped ED OT with the distinct ED2-ED5 origin areas. DO2 .. DO5: distal origin edges ED2 .. ED5. DO2: the ED2 OT splits from the common bipennate ED2-ECRB OT sheet (see Fig. 7.A) to continue with a small unipennate OT (not well visible in picture) as modeled in Fig. 2.b. S: supinator.

D. Specimen of A, ED5 elevated, showing EDM arising from the ulnar side of the bipennate ulnar ED OT. White arrow: EDM OT splits from ED OT and continues as a small unipennate OT (modeled in Figure 2.b). DOM: distal edge EDM OT.

Figure 6
Extensor digiti minimi (EDM) OT compartments, superficially opened to show the EDM inside. Black arrows: proximal EDM compartment edges. Specimens A-C have long EDM compartments, D has a short compartment.

A. Specimen of Fig. 5.A. DOM: distal edge unipennate EDM OT slip, split of from ulnar ED OT. DO5: distal edge ED5 OT.

B. The ulnar EDM origin from the ECU OT is typically shorter than from the ED OT.
DUOM: distal edge ulnar EDM origin. DROM: distal edge radial EDM origin (from ulnar ED OT). 4/5: ED4 and ED5 muscle bellies not separable.

C. Very long EDM compartment. ED4 and ED5 muscle bellies not well separable.
White arrow: cross-over muscle belly from ED2 origin area (not in view) to ED3 end tendon.

D. Short EDM compartment. Much longer radial (DROM) than ulnar (DUOM) EDM origin. ED4 and ED5 well separable. White arrow: small crossover muscle belly from ED3 origin area to ED2 end tendon.
Figure 7

Deep finger extensors

A. White dotted lines outline EI, EPL and APL/EPB. EI and EPL muscle bellies reach very distal in both specimens A and B. The EI origin in A starts much more proximal than in B. F: fascia, forming the radial border of ED compartment, bridging APL and EPB. The radial OT complex of ED and ECRB is raised, after section of muscles distal to OT, showing it only attaches to the lateral epicondyle. White dotted lines outline the ECRB OT sheet. Black dotted line marks common bipennate OT part (BOT) of ED/ECRB. The ECRB arises at the backside. The ED2 at the front side (2). The ED3 has been removed (3). \( \text{ROT}_{\text{ECRB}} \): deep unipennate radial expansion of ECRB OT (‘floor’ of ECRB OT compartment). \( \text{SOT}_{\text{ED}} \): superficial (unipennate) ED OT with muscle fibers of ED3 and ED4 removed, severed at 4’ from ulnar part of ED OT (UOT\(_{\text{ED}}\)). ANC: Anconeus compartment, with anconeus removed. ECU is dissected from its OT compartment. S: supinator.

B. Specimen of Fig. 4.B. ECU is retracted, showing the underlying ulna, with OT fibers of EPL and EI arising from the dorsal ulna crest (in this specimen the radial ECU OT could easily be separated from the ulna and retracted. No ECU muscle fibers arose directly from the ulna). The EI origin starts much more distal than in A. White arrow: distal edge ECU muscle fiber insertions at ulnar side of ECU tendon (see Figure 8). UOT\(_{\text{ED}}\): ulnar ED OT.

Figure 8

ECU model, longitudinal cross-section. The radial (deep) OT is long. The ulnar (superficial) OT is relatively short. Therefore, the ECU ET, as compared to radial, becomes distally superficially bare of muscle fibers over a length \( \text{L DUI-DRI} \). DUI, DRI: distal edge of ulnar and radial muscle fiber insertion, resp. PFL: projected muscle fiber length.
**Figure 9**
Location of origins (dark gray bars) and distal reach of muscle bellies (light grey bars) of finger and wrist extensors relative to Humerus-Radius Joint (HRJ). Mean and standard deviation of measurements normalized to radius length (%) in ten specimens. Muscles in anatomic order from radial to ulnar. ECUr, ECUu: radial side of OT compartment reaches more distal than ulnar (superficial) side. Halter figures: bipolar surface electrode symbols, scaled to 20mm between dot centers, at proposed optimal anatomic length locations (see text).

**Figure 10**
Neurovascularization of finger extensors and ECU. White dots mark nerves. Black dots mark arteries (not all shown). 2 .. 5: ED2 .. ED5 muscle bellies. EDM: extensor digiti minimi. N: radial motor nerve, emerging from beneath supinator (S), forming a plexus innervating all finger extensors and ECU (ECU nerve branch not visible). Distinct nerve branches n₂ .. n₅ innervate ED2 .. ED5, and further EDM, EI, APL/EPB. \( n_{dio} \): dorsal interosseus nerve. A: arterial plexus distal to supinator. \( A_m \): arteries perforating the interosseus membrane from palmar to dorsal, splitting in sub-branches.

**Figure 11**
Proposed bipolar surface EMG electrode locations on finger and wrist extensors.
A. Electrode locations on forearm surface. White dotted lines outline surface area of ED2, ED3, ED4 and EDM. White striped lines mark proximal or distal muscle origins or distal muscle belly edges.
B. Forearm, in same position as A, showing that ED2 and ED4 electrodes are distal to the distal ED3 muscle belly edge.
C. Removal of ED3 muscle belly, showing that the ED3 electrode is proximal to ED2 and ED4 origins.

D. Projection of electrodes on the deep extensors. ECU is retracted (see Fig. 7.B).

  EPL and proximal EI are deep to EDM electrodes. APL is deep to ED2 and ED4 electrodes. No muscle directly underlies the ED3 electrodes. EI electrodes are very distal and ulnar, but still cover the EI muscle belly.

**Figure 12**

A single neuroprosthesis extensor electrode cannot likely evenly stimulate ED and EDM. Electrode e₁ would stimulate ED3 exclusively. e₂ would stimulate ED4, ED2 only proximally, little of ED3 and very little of EDM. To reach ED3, e₂ would have to be placed deep, which is near the radial motor nerve plexus RN (dotted white circle, C). e₃ would stimulate ED5 rather than ED4 (radiating to ED2 and EDM), but none of ED3.

**Figure 13**

Uniform ED-EDM stimulation by multiple neuroprosthesis electrodes. All electrode positions are on superficial muscle parts, which can be superficially per-operatively stimulated.

A-C: three electrodes. e₁ stimulates ED3. e₂ stimulates ED2 and partly ED4/5 (mostly ED5). e₃, placed at the bipennate ulnar ED OT, stimulates ED4/5 and EDM.

D-F: four electrodes provide better cover than A. e₁ stimulates ED3; e₂ stimulates ED4; e₃ stimulates ED2, and partly distal ED4 and ED5; e₄ stimulates EDM and partly ED5. However, e₂ is closer to the radial nerve plexus RN, although, when e₂ is placed superficially in ED4, the distal ED3 muscle belly and ET remains between electrode and RN plexus.
Legends with the Tables

Table 1
Measured specimens, normative values, maximum width of ED and width of ED where the proximal edge of the APL crosses the radial edge of the ED (Fig. 4.c).

Table 2
Mean and standard deviation of normalized positions (% of radius length) of proximal and distal origin edges, and distal muscle fiber insertion edges, of all extensor muscles and ED muscle parts, relative to the humerus-radius joint (HRJ) (Fig. 3). Last columns: maximum surface widths of superficial muscles and ED muscle parts. (*) ED2 and ED4 were measured where the proximal APL edge crosses the radial ED3 edge (Fig. 4.C). ECUr and ECUu: separate data for radial and ulnar side of ECU OT compartment (see text and Fig. 8).
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177x45mm (600 x 600 DPI)
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57x22mm (600 x 600 DPI)
Figure 4 Superficial aspect of extensor digitorum communis (ED) A. Posterior fascia antebrachii. White dotted lines: thickened connective tissue outlining ED and EDM compartments. Black arrow: proximal edge of EDM compartment, identifiable through the opaque fascia over its entire length. Double white arrow: width ED. OT: longitudinal tendon fibers of superficial ED OT sheet beneath fascia. White arrows: distal edge OT sheet, reaching more distal ulnarly. LE: lateral epicondyle. B. Removal of fascia antebrachii up to OT. In this specimen the superficial ED OT was very long (compare with white arrows in A). White and black arrows: aerolar tissue lines separating ED2 (2) and ED4/5 (4/5), and ED4/5 and EDM, respectively. ECRL, ECRB: extensor carpi radialis longus and brevis, APL: abductor pollicis longus, ECU: extensor carpi ulnaris. LE: lateral epicondyle. C. Detail of B (rectangle). ED2 and ED4/5, and ED4/5 and EDM separated at the aerolar tissue lines marked in B. Double white arrows: widths of ED2 and ED4/5 where the proximal APL edge crosses the radial ED2 edge; and greatest EDM width (values in Table 2). T2 .. T5: ED2 .. ED5 end tendons. TEPL: extensor pollicis longus ET. D. Retraction of ED2 and ED4 shows the underlying, independent, short ED3 muscle belly with its long end tendon.

177x63mm (600 x 600 DPI)
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Table 2. (1) Mean and standard deviation of positions as % of radius lengths of proximal and distal muscle origins, and distal insertion, relative to HRJ (=0).

(2) Muscle surface width

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