Architectural design of the human intrinsic hand muscles

The architectural features of twenty different muscles (18 intrinsics and 2 thumb extrinsics, \( n = 180 \) total muscles) were studied. Muscle length, mass, fiber pennation angle, fiber length, and sarcomere length were determined. From these values, physiologic cross-sectional area and fiber length/muscle length ratio were calculated. Intrinsic muscle lengths were relatively similar to one another, which we interpreted as representing a space constraint within the hand. However, several specialized architectural designs were observed: lumbrical muscles had an extremely high fiber length/muscle length ratio, implying a design toward high excursion. The first dorsal interosseous and adductor pollicis had physiologic cross-sectional areas comparable to those of extrinsic muscles and much greater than those of the other intrinsic muscles. The interosseous muscles had relatively high physiologic cross-sectional areas with low fiber length/muscle length ratios, suggesting their adaptation for high force production and low excursion. Taken together, these observations illustrate the underlying structural basis for the functional capacities of the intrinsic muscles. (J Hand Surg 1992;17A:804-9.)

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The architecture of skeletal muscle is its most important functional determinant. Architecture is defined as the arrangement of muscle fibers relative to the axis of force generation. The most important architectural properties are muscle fiber length and physiologic cross-sectional area (PCSA). This is because muscle excursion and velocity are directly proportional to muscle fiber length while isometric muscle force is directly proportional to muscle PCSA. Because of these direct structure-function correlations, studies of muscle architecture provide insight into muscle functional properties. Recently the architectural properties of the forearm muscles were studied, and these muscles were found to have unique architectural designs. Architectural differences, and therefore functional specialization, were found both between and within functional muscle groups (i.e., wrist movers were architecturally different from digital flexors and extensors, and some wrist movers differed from each other).

The intrinsic muscles of the hand are of paramount importance in efficient hand function. Electromyographic studies have provided insights into the unique functions of the intrinsic hand muscles. However, few investigators have characterized architectural and functional properties of the intrinsic muscles. Thus the purpose of this study was to measure the architecture of the intrinsic muscles of the hand. An understanding of muscle architectural specialization has implications for surgical procedures involving muscle and tendon transfer, biomechanical modeling, prosthesis design, and analysis of normal function.

Methods

Each of the intrinsic hand muscles and two extrinsic muscles of the thumb were studied. One hundred eighty muscles (20 different muscles from nine different cadaver limbs) were prepared for architectural determination. These included the abductor digiti minimi (AbDM), abductor pollicis brevis (AbPB), abductor pollicis longus (AbPL), adductor pollicis (AddP), dorsal interosseous (DI1-DI4), extensor pollicis brevis (EPB), flexor digiti minimi (FDM), flexor pollicis brevis (FPB), lumbrical (L1-L4), opponens digiti minimi (ODM), opponens pollicis (OpP), and palmar interosseous muscles (PI2-PI4).

Muscle architecture was determined according to the methods developed by Sacks and Roy, as reported recently for forearm muscles. Briefly, this method involves in situ formalin fixation of cadaver upper extremities and subsequent muscle dissection and muscle fiber microdissection. Architectural properties determined included muscle length (ML), fiber length (FL), physiologic cross-sectional area, and fiber length/muscle length (ML/FL) ratio.

For comparison with one another, intrinsic muscles were placed into one of five anatomic muscle groups (i.e., thenar, hypothenar, lumbral, dorsal interosseous, and palmar interosseous muscles). Data are presented in the text as mean values ± standard deviation.

Results

Gross anatomy. Dissected hands revealed variable insertions of the interosseous and lumbral muscles. Interosseous muscles attached to the metacarpal bones in patterns as previously reported. Attachment to adjacent metacarpal bones was more common in DI3 and DI4. Some of the lumbrical muscles had origins from adjacent flexor digitorum profundus (FDP) tendons and peritendinous connective tissue, as stated in the literature. The second lumbrical of one hand was grossly smaller than the others of that hand and appeared shorter and tenuous. This muscle was included in the study and accounts for the larger variability in the data for that muscle. It was believed that the first palmar interosseous muscle was found in one hand, but this was not found in any of the other specimens.

Architectural features. Intrinsic muscles demonstrated significant architectural differences (Table 1). Intrinsic ML ranged from 48 to 68 mm with a coefficient of variation of 44% (Fig. 1). Interestingly, this was relatively more variable than forearm muscles that had a coefficient of variation of 31%. We observed relatively large differences in ML between the intrinsic muscles (64.5 ± 26.8 mm, n = 180) and the forearm muscles (162 ± 48.6 mm, n = 192).

Despite the two- to threefold ML difference, intrinsic muscle FLs (32.3 ± 13.3 mm, n = 178; Fig. 2) were similar to forearm muscle FLs (54.6 ± 20.2 mm, n = 192). Intrinsic muscle FLs fell into three groups (Fig. 2): lumbricals had the longest fiber lengths (40 to 48 mm), followed by the thenar and hypothenar muscles (34 to 41 mm) and then by the interosseous muscles (23 to 31 mm). The exception to this trend was the ODM, which had a fiber length of 19 mm.

The intrinsic muscles of the hand had relatively low muscle masses (Fig. 3). The mass of the AddP (1.94 gm) was the largest of the intrinsic muscles. The DI5 were next largest, followed by the PI, thenar, and hypothenar muscles. The lumbrical muscles had the low-
Table I. Architectural properties measured

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Muscle mass (gm)</th>
<th>Muscle length (mm)</th>
<th>Fiber length (mm)</th>
<th>Penetration angle (degrees)</th>
<th>Cross-sectional area (cm²)</th>
<th>FL/ML ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>AbDM</td>
<td>3.32 ± 1.67</td>
<td>68.4 ± 6.5</td>
<td>46.2 ± 7.2</td>
<td>3.9 ± 1.3</td>
<td>0.89 ± 0.49</td>
<td>0.68 ± 0.10</td>
</tr>
<tr>
<td>AbPB</td>
<td>2.61 ± 1.19</td>
<td>60.4 ± 6.6</td>
<td>41.6 ± 5.6</td>
<td>4.6 ± 1.9</td>
<td>0.68 ± 0.28</td>
<td>0.69 ± 0.09</td>
</tr>
<tr>
<td>AbPL</td>
<td>9.96 ± 2.01</td>
<td>160.4 ± 15.0</td>
<td>58.1 ± 7.4</td>
<td>7.5 ± 2.0</td>
<td>1.93 ± 0.59</td>
<td>0.36 ± 0.05</td>
</tr>
<tr>
<td>AddP</td>
<td>6.78 ± 1.84</td>
<td>54.6 ± 8.9</td>
<td>34.0 ± 7.5</td>
<td>17.3 ± 3.4</td>
<td>1.94 ± 0.39</td>
<td>0.63 ± 0.15</td>
</tr>
<tr>
<td>Di 1</td>
<td>4.67 ± 1.17</td>
<td>61.9 ± 2.5</td>
<td>31.7 ± 2.8</td>
<td>9.2 ± 2.6</td>
<td>1.50 ± 0.40</td>
<td>0.51 ± 0.05</td>
</tr>
<tr>
<td>Di 2</td>
<td>2.65 ± 1.01</td>
<td>62.8 ± 8.1</td>
<td>25.1 ± 6.3</td>
<td>8.2 ± 3.1</td>
<td>1.34 ± 0.77</td>
<td>0.41 ± 0.13</td>
</tr>
<tr>
<td>Di 3</td>
<td>2.01 ± 0.60</td>
<td>54.9 ± 4.6</td>
<td>25.8 ± 3.4</td>
<td>9.8 ± 2.8</td>
<td>0.95 ± 0.45</td>
<td>0.47 ± 0.07</td>
</tr>
<tr>
<td>Di 4</td>
<td>1.90 ± 0.62</td>
<td>50.1 ± 5.3</td>
<td>25.8 ± 3.4</td>
<td>9.4 ± 4.2</td>
<td>0.91 ± 0.38</td>
<td>0.52 ± 0.11</td>
</tr>
<tr>
<td>EPB</td>
<td>2.25 ± 1.36</td>
<td>105.6 ± 22.5</td>
<td>55.0 ± 7.5</td>
<td>7.2 ± 4.4</td>
<td>0.47 ± 0.32</td>
<td>0.54 ± 0.13</td>
</tr>
<tr>
<td>FDM</td>
<td>1.54 ± 0.44</td>
<td>59.2 ± 10.4</td>
<td>40.6 ± 13.7</td>
<td>3.6 ± 1.0</td>
<td>0.54 ± 0.36</td>
<td>0.67 ± 0.17</td>
</tr>
<tr>
<td>FBP</td>
<td>2.58 ± 0.56</td>
<td>57.2 ± 3.7</td>
<td>41.5 ± 5.2</td>
<td>6.2 ± 4.5</td>
<td>0.66 ± 0.20</td>
<td>0.73 ± 0.08</td>
</tr>
<tr>
<td>Lum 1</td>
<td>0.57 ± 0.19</td>
<td>64.9 ± 10.0</td>
<td>55.4 ± 10.2</td>
<td>1.2 ± 0.9</td>
<td>0.11 ± 0.03</td>
<td>0.85 ± 0.03</td>
</tr>
<tr>
<td>Lum 2</td>
<td>0.39 ± 0.22</td>
<td>61.2 ± 17.8</td>
<td>55.5 ± 17.7</td>
<td>1.6 ± 1.3</td>
<td>0.08 ± 0.04</td>
<td>0.90 ± 0.05</td>
</tr>
<tr>
<td>Lum 3</td>
<td>0.37 ± 0.16</td>
<td>64.3 ± 8.9</td>
<td>56.2 ± 10.7</td>
<td>1.1 ± 0.8</td>
<td>0.08 ± 0.04</td>
<td>0.87 ± 0.07</td>
</tr>
<tr>
<td>Lum 4</td>
<td>0.23 ± 0.11</td>
<td>53.8 ± 11.5</td>
<td>50.1 ± 8.4</td>
<td>0.7 ± 1.0</td>
<td>0.06 ± 0.03</td>
<td>0.90 ± 0.05</td>
</tr>
<tr>
<td>ODM</td>
<td>1.94 ± 0.98</td>
<td>47.2 ± 3.6</td>
<td>19.5 ± 4.1</td>
<td>7.7 ± 2.9</td>
<td>1.10 ± 0.43</td>
<td>0.41 ± 0.09</td>
</tr>
<tr>
<td>OpP</td>
<td>3.51 ± 0.89</td>
<td>55.5 ± 5.0</td>
<td>35.5 ± 5.1</td>
<td>4.9 ± 2.5</td>
<td>1.02 ± 0.35</td>
<td>0.64 ± 0.07</td>
</tr>
<tr>
<td>PI 2</td>
<td>1.56 ± 0.22</td>
<td>55.1 ± 5.0</td>
<td>25.0 ± 5.0</td>
<td>6.3 ± 2.2</td>
<td>0.75 ± 0.25</td>
<td>0.45 ± 0.08</td>
</tr>
<tr>
<td>PI 3</td>
<td>1.28 ± 0.28</td>
<td>48.2 ± 2.9</td>
<td>26.0 ± 4.3</td>
<td>7.7 ± 3.9</td>
<td>0.65 ± 0.26</td>
<td>0.54 ± 0.08</td>
</tr>
<tr>
<td>PI 4</td>
<td>1.19 ± 0.33</td>
<td>45.3 ± 5.8</td>
<td>23.6 ± 2.6</td>
<td>8.2 ± 3.5</td>
<td>0.61 ± 0.23</td>
<td>0.52 ± 0.10</td>
</tr>
</tbody>
</table>

Values represent mean ± standard deviations.
Abbreviations: AbDM = abductor digiti minimi; AbPB = abductor pollicis brevis; AbPL = abductor pollicis longus; AddP = adductor pollicis; Di1-Di4 = dorsal interosseus muscles; EPB = extensor pollicis brevis; FDM = flexor digiti minimi; FBP = flexor pollicis brevis; L1-L4 = lumbrical muscles; ODM = opponens digiti minimi; OpP = opponens pollicis; PI2-PI4 = palmar interosseous muscles.

est masses of all muscles of the forearm and hand, ranging from only 0.23 to 0.57 gm. Generally, the intrinsic muscle masses were small compared with the forearm muscles with the exceptions of the AddP and Di1.

Physiologic cross-sectional area varied greatly between the intrinsic muscles and was generally much less than the muscles of the forearm. AddP (1.10 cm²) and Di1 (1.50 cm²) had the largest PCSAs, as well as the greatest masses. These PCSAs were comparable to the PCSA of extensor carpi radialis longus (ECRL), flexor carpi radialis (FCR), FDSI, and FDSR and much greater than the individual digital extensors\(^2\)\(^{-3}\) (Fig. 4). Lumbricals had extremely low PCSAs (0.11 to 0.06 cm²), the lowest in the upper extremity. Their PCSAs were only one tenth to one twentieth of the PCSA of the FDPs (PCSA 2.0 cm²).

FL/ML ratios of all the intrinsic muscles were high in comparison to those seen in the forearm muscles (Fig. 5). The lumbrical muscles had the highest ratios (0.85 to 0.90), the largest measured to date in the upper extremity. The thenar and hypothenar groups (0.41 to 0.73) were intermediate for the intrinsic muscles. The interosseus muscles had the lowest FL/ML ratios of the intrinsic muscles (0.41 to 0.55), which were comparable to muscles in the forearm.

Discussion

The major finding of this study was that the intrinsic muscles of the hand were highly specialized in terms of architectural properties. Differences in architectural design were demonstrated between and within functional muscle groups by large differences in parameters measured (i.e., mass of Di1 versus Di4 and
FL of OpP versus ADM). Small standard deviations for most measurements, however, showed consistency of architecture for a given muscle between specimens.

In general, absolute muscle lengths of the intrinsic muscles were similar. Since muscle length is not necessarily consistent between synergistic muscles, this may simply represent a space limitation within the hand itself. Thus the intrinsic muscles had an average muscle length of 65 mm, whereas extrinsic muscle length was almost three times greater (162 mm). In spite of this significant difference in muscle length between extrinsic and intrinsic muscles, no such dramatic distinction was observed in fiber length. For example, lumbral fiber lengths were similar in absolute magnitude to the fiber lengths of the FDP, flexor digitorum superficialis, and ECRB muscles.

The lumbral muscles provided several extreme examples of architectural adaptation. Lumbral muscle fibers extended 85% to 90% of the muscle length. Of the 45 different muscles that we have studied in the human upper limb and 29 different muscles in the rabbit hindlimb, this is the highest FL/ML ratio that we have encountered. We interpret this as indicating that lumbral muscles are designed for high excursions. The result of this adaptation is a much flatter, broader length-tension curve that would allow relatively constant contractile force over a long range of fiber lengths, depending on the position of the FDP tendon. This interpretation has intuitive appeal since the lumbricals
are the only muscles in the body whose origin and insertion are tendons. It could be argued that long lumbrical muscle fiber length might facilitate active muscle contraction, even during FDP contraction, by allowing the lumbrical origin to move without large changes in sarcomere length. If lumbrical fiber lengths were very short, FDP excursion could stretch lumbrical sarcomeres to the point where they were unable to generate active force.

The most variable parameter between intrinsic muscles was their physiologic cross-sectional area. PCSA is proportional to muscle maximum isometric tension. At one extreme, the lumbrical PCSA was 0.1 cm², while at the other extreme the AddP PCSA was almost 2.0 cm². Generally, PCSAs of the intrinsic muscles were the lowest of all those measured in the upper limb, with the exception of those muscles that had no extrinsic synergist. For example, AddP and DI1 are the primary providers of their functions in the hand and are responsible for key pinch, which requires the ability to generate high forces. Also, DI1 abducts against the cumulative flexion forces of the FPL, FPB, and OpP in opposition and during key pinch. These muscles must also function to maintain key pinch during forearm supination and pronation. If supination or pronation strength of the forearm were significantly stronger than key pinch strength in the hand, forearm rotation would overpower pinch and cause release of the object.

The FL/ML ratio can be seen as a relative measure of design preference for excursion (high ratio) or force production (low ratio). The intrinsic muscles have relatively high FL/ML ratios, representing a design bias toward excursion and velocity production and a relative bias against force production. The interosseous muscles had the lowest FL/ML ratio of the intrinsic muscles, but the ratio was surprisingly high for their pennation. This may indicate that they require a minimum fiber length to provide their function despite the confines of their position, and their design may represent an architectural compromise to ensure adequate strength while not compromising joint range of motion.

Other authors have studied muscle architecture directly⁶ or have extrapolated values (i.e., FL) from muscle experiments (i.e., in vivo tendon excursions).¹³,¹⁴ Our fiber length data agree well with the summary provided by Smith and Hastings¹⁵ for estimating intrinsic muscle excursions. This may be because the intrinsic muscle data they used were from Brand,⁹ whose methods were similar to ours. There were, however, large differences between our fiber length data and the excursion estimates reported for the wrist movers, brachioradialis, and thumb extrinsics.¹⁵ These differences probably result from data collected by determining tendon excursion in surgical patients, independent of architectural determination.

Comparison of our PCSA data with the relative force capability of the intrinsic muscles offered by Smith and Hastings revealed large differences. The force estimate for the interossei, AbPL, EPB, ECRB, PL, and PT were less than predicted with our data. Their force predictions for the lumbrical muscles, FDSS, digital extensors, and BR, however, were much higher than we would predict. This could be because Smith and Hastings used data that others had based on muscle mass, a poor predictor of muscle force.

This work offers data representative of the functional capability of the intrinsic muscles of the hand based on gross and microscopic measurements. These data provide insight into the “design” of muscle and may provide additional information useful in biomechanics, tendon transfer, and rehabilitation.

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REFERENCES
2. Lieber RL, Fazeli BM, Botte MJ. Architecture of selected


