

ARE THE EXTRINSIC MUSCLES BETTER SUITED FOR SIGNALING JOINT ANGLES OR FINGER TIP LOCATION?

James Biggs¹, Ken Horch¹, Frank Clark²

¹Department of Bioengineering, 2480 MEB, University of Utah, Salt Lake City, UT 84112

²Department of Physiology and Biophysics, University of Nebraska Medical School, Omaha, NE 68105

¹E-mail: sbiggs@eng.utah.edu

ABSTRACT

We used a biomechanical model of the human long finger to determine whether the extrinsic muscles are better suited for estimating the finger's joint angles or for estimating location of the finger tip. We found that two of the extrinsic muscles together could provide information sufficient to directly determine the location of the finger tip relative to MetaCarpoPhalangeal (MCP) joint, without having to determine any of the finger's joint angles. We also found that for some finger positions the extrinsic muscles provide ambiguous information about the finger's joint angles. These results suggest that the biomechanics of the finger and the extrinsic muscles lend themselves more readily to a determination of finger tip location than to a determination of joint angles. In light of these results it seems possible that human proprioception in the hand may reflect a sense of finger tip location, not joint angles.

INTRODUCTION

Much research on proprioception has proceeded on the tacit assumption that the nervous system senses the angles of individual joints. A common paradigm, for example, is a matching task in which the joint angle in a reference limb is set either actively by the subject or passively by the experimenter, and the subject is then asked to match that joint angle with the other limb [1, 2]. Despite its wide spread use, it seems possible that this joint angle paradigm may not reflect the normal operation of the sensory-motor system.

We investigated the possibility that the fingers are sensed not in terms of their joint angles, but directly in terms of the position of the finger tip. To do so, we used cadaver data to develop a biomechanical model of the human long finger. Given the angles the finger's three joints, this model used estimates of the finger's link lengths to calculate the location of the finger tip, and estimates of the flexor and extensor pulley radii to calculate the lengths of the extrinsic finger muscles. The lengths of these muscles were of interest because the bulk of proprioception research has shown that the muscle spindles, which vary their firing rate according to the length of the muscle, are the source of static position sense [3, 4].

Thus the model provided a way for us to determine what sort of information the finger's proprioceptive sensors -- the extrinsic muscles -- could provide the central nervous system about joint angles, and about finger-tip location. We did not model all finger muscles. Rather we focused our attention on those which operate the distal joints, as these were more likely to provide useful information about finger tip location. Specifically, the muscles modeled were: the Flexor Digitorum Superficialis (FDS), Flexor Digitorum Profundus (FDP), and Extensor Digitorum Longus (EDL). These muscles all originate in the forearm, project their tendons across the wrist, the MetaCarpoPhalangeal joint (MCP), and the Proximal InterPhalangeal joint (PIP). The FDS and medial band of the EDL insert on the second phalange, while the FDP and lateral band of the EDL cross one more joint, the Distal InterPhalangeal (DIP), before inserting on the distal phalange.

We found that information from just two of the extrinsic muscles can provide an unambiguous estimate of finger tip location. We also found that there are some positions of the finger where the extrinsic muscles cannot provide an unambiguous estimate of the finger's joint angles.

METHODS

General: We first gathered cadaver data and used it to develop a biomechanical model of the finger, which facilitated two experiments. The first experiment was designed to determine whether direct sensing of finger tip location is possible. We approached the problem backward. First we used a brute force search to find a representative sample of all finger tip locations which could produce a fixed length of one muscle, then bounded the cluster of finger tip locations which qualified. We reasoned that from the nervous system's perspective, knowing the length of the muscle was sufficient to determine that the finger tip lay somewhere within the bounded region. We repeated the process for different muscles at different lengths.

The second experiment was designed to determine whether judgment of the finger's joint angles is ever impossible, based on the lengths of the extrinsic muscles. We accomplished this by explicitly searching for pairs of ambiguous finger positions (i.e. substantially different in at

least one joint angle, but indistinguishable on the basis of the extrinsic muscle lengths taken as a set).

Cadaver data and modeling: We made measurements relating joint angles of the long finger to lengths of the extrinsic muscles for the right long finger of an adult male cadaver, then fit these measurements to a non-linear tendon excursion model similar to that proposed by An [5]. This model assumed fixed wrist position, constant abduction/adduction posture of the MCP joint, and constant muscle load.

Non-linearity of the model prevented us from finding analytic answers to our questions, so we used MATLAB™ to construct and search a brute force look-up table. For an adult's normal active range of long finger motion with no hyper-extension, this table represented all possible sets of joint angles on a 1° grid. For each pose in the table we used the model to calculate the lengths of the extrinsic muscles. This exercise generated a matrix with ~640,000 rows of finger positions, 3 columns of joint angles and 3 columns of muscle lengths, comprising $\sim 4 \cdot 10^6$ elements.

Bounds on finger tip location: In order to determine whether the nervous system can derive finger tip location directly from the lengths of the extrinsic finger muscles, we first selected an initial finger pose and a muscle of interest. We calculated the target muscle length which would result from that pose, then searched our look-up table for all finger positions having a muscle length within 25 μm of our target muscle length.

We calculated the finger tip location for each of these poses using standard anthropometric data on link lengths scaled to the length of our cadaver finger. This generated a cluster of points in the finger's work space scattered over an area which we bounded with a line. From the nervous system's point of view, knowing the length of the muscle to $\pm 25 \mu\text{m}$ is sufficient to place the fingertip somewhere inside the bounded area. We repeated this process for different muscles and different positions. We limited the search to those positions which can be achieved without imposing an outside load on the finger (i.e. DIP flexion < PIP flexion).

In order to determine what information about finger tip location can be derived from a pair of extrinsic muscles we repeated the process using targets that were pairs of muscle lengths. When we compared the size and shape of bounds found in these two-muscle searches with those generated by bounding the intersection of two one-muscle searches, we found no marked difference.

When we searched our look-up table using triplets of muscle lengths as targets, we found no matches for the target set of muscle lengths, unless we picked a muscle lengths which corresponded to a joint angle ambiguity, as described below.

Joint angle ambiguity: In order to determine whether unambiguous judgment of the finger's joint angles is ever impossible, based on the lengths of the extrinsic muscles taken as a set, we explicitly searched for cases in which such an attempt would fail. This would occur if there were two or more finger positions substantially different in their joint angles, but indistinguishable on the basis of muscle lengths. Such a pair need not have identical muscle lengths, but merely lengths indistinguishable based on the firing rate of muscle spindles, which have finite sensitivity to stretch and non-zero background noise. The literature on muscle spindle sensitivity places the detection threshold for a very slow change in muscle length in the 5-25 μm range. Accordingly we searched at both 5 and 25 μm .

RESULTS

Cadaver data and modeling: The data gathered from the cadaver finger consisted of ~75,000 poses in all. We verified the internal consistency of the data by comparing measured tendon excursions at identical finger poses assumed during sweeps of different joints. The data set was internally consistent to $\pm 2.5\%$ of the extrinsic muscle's working range. The model's fit to these data was satisfactory, with an overall RMS difference between modeled and measured values of 2.0% of the muscle's working range.

Bounds on finger tip location: We found that useful information about finger tip location could be extracted from the length of a single extrinsic muscle. If the finger tip was on one of the three black dots in Figure 1, then information from the EDL was sufficient to determine that the finger tip lay somewhere within the region around that dot bounded by the dashed line. Because these bounded areas were long, thin, and pointed roughly toward the MCP joint, this muscle gave good information about the direction of the finger tip from the MCP joint. It could not, however, provide information about how far the finger tip was from the MCP joint.

Unlike the bounded areas of EDL, those of the FDP (solid lines) did not point toward the MCP joint. Since the finger tip had to lie somewhere within the intersection of the two bounded areas, EDL and FDP were sufficient to accurately specify finger tip location within the work space. The results illustrated in Figure 1 were typical of those found throughout the work space.

For most finger positions, adding information from the third muscle, FDS, was sufficient to collapse the bound on the location of the finger tip down to a point. In these cases only one set of joint angles, and hence only one finger tip location corresponded to the lengths of the three muscles. Exceptions

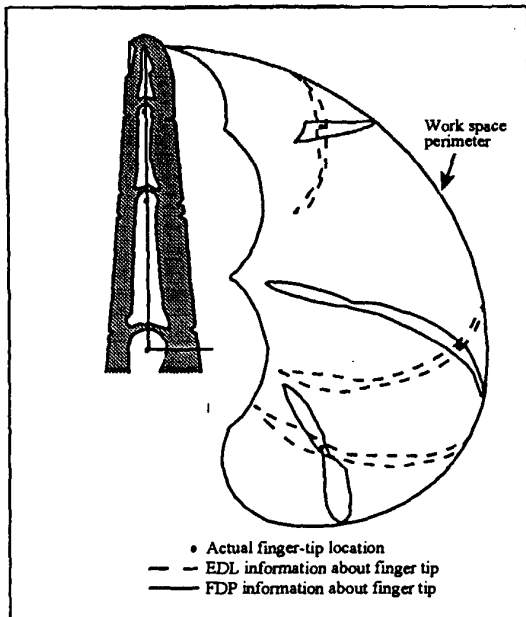


Figure 1

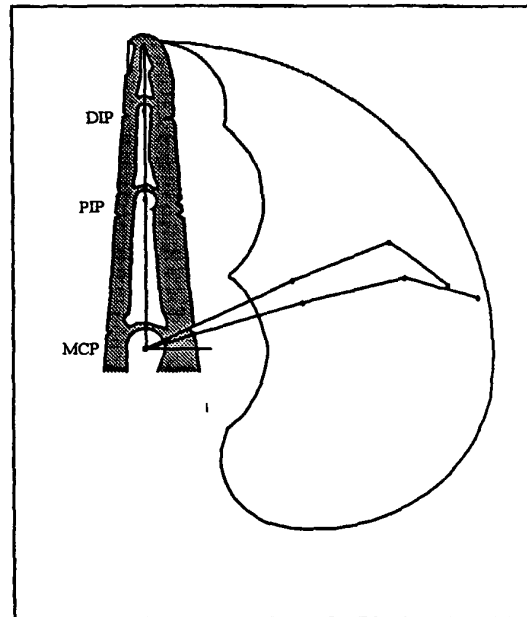


Figure 2

to this pattern occurred when all three muscle lengths corresponded to an "ambiguous finger position." At an ambiguous finger position adding information from the third muscle did not collapse the bounds on finger tip location to a point, but left some uncertainty in finger tip location (Figure 2). The circumstances under which ambiguous finger positions occurred are described more fully below.

Joint angle ambiguity: Our search for pairs of finger positions with joint angles indistinguishable on the basis of extrinsic muscle lengths showed that such pairs exist, but only under very particular circumstances. Like the example illustrated by the stick-fingers in Figure 2 these ambiguities occurred only when one or both of the positions in the pair had DIP-joint flexion greater than PIP-joint flexion – a posture which can only be achieved when an outside load is imposed on the finger. In all ambiguities MCP joint flexion was large ($60^\circ - 91^\circ$), and PIP joint flexion small ($0^\circ - 36^\circ$).

These limited joint ranges contributed to making the ambiguities rare. Using a $25 \mu\text{m}$ threshold, of the $2.2 \cdot 10^{11}$ pairs of finger positions considered in our search only 1 in every $4.7 \cdot 10^5$ pairs of finger positions were indistinguishable. Repeating the search with a $5 \mu\text{m}$ limit reduced the frequency to 1 in every $2.2 \cdot 10^6$ but did not alter the range of joint angles in which the ambiguities occurred. Uncertainty of the joint angles at an ambiguous finger position was often large: up to 20° and 65° for the MCP and DIP joints respectively, while uncertainties in PIP angle remained small ($< 4^\circ$).

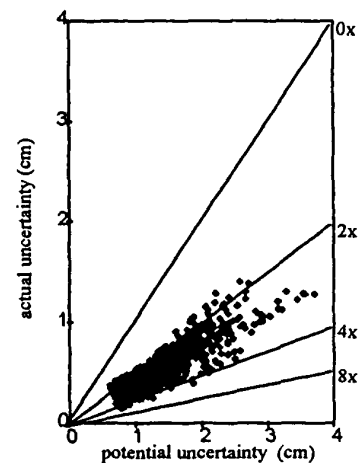


Figure 3

We noted that despite the relatively large uncertainties in MCP and DIP-joint angle at ambiguous finger positions, knowledge of the location of the finger tip was not comparably degraded. To move between pairs of ambiguous positions, the MCP and DIP joints had to rotate in opposite directions, each offsetting the other's contribution to displacing the finger tip. Figure 3 quantifies this phenomenon by plotting the actual uncertainty in finger tip location against the uncertainty in location which would have occurred had all three finger joints rotated in the same direction. Counter-rotation of the joints reduced most uncertainties in finger tip location 2-4x.

DISCUSSION

General: In this study we perform two experiments designed to determine whether the extrinsic muscles have biomechanics better suited for estimating finger tip position, or finger joint angles.

Our first experiment shows that the extrinsic muscles can provide a direct estimate of the location of the finger tip in the work space. No intermediate estimates of joint angles are required. Knowing the lengths of just two muscles (FDP and EDL) is sufficient to know the location of the finger tip to within a small tolerance (Figure 1).

Our second experiment shows that sometimes the extrinsic muscles provide ambiguous information about finger joint angles (Figure 2). When these ambiguous positions occur, they degrade knowledge of joint angle more severely than they degrade knowledge of finger tip position (Figure 3). Together, these two experiments suggest that the extrinsic muscles may be better suited for estimating finger tip position than for estimating finger joint angles.

Implications for proprioception: Ours is not the first study to suggest that proprioceptive sense may not be joint angle sense. Soechting, for example, reports that subjects are better at matching the orientation of their forearms in space than they are at matching the actual flexion angle of the elbow joint [6]. Based on our results we speculate that proprioceptive sense may reflect direct knowledge of the location of a more distal point on the body (e.g. the finger tip) with respect to a more proximal point (e.g. the center of rotation of the MCP joint).

Implications for control: The observation that two muscles, EDL and FDP, can give good information about the location of the finger tip has interesting consequences for control of the finger. At a biomechanical level, constraints on sensing limb position and constraints on setting limb position are equivalent, because the muscles are responsible for both. Thus Figure 1 implies that setting the lengths of the EDL and FDP is sufficient to constrain the location of the finger tip to a very small region of the work space.

This result is unexpected because Greubler's constraint equation [7] requires a minimum of three linearly independent tendons to stabilize a three-joint planar mechanism like the finger. EDL and FDP effectively circumvent this requirement. Although fixing their lengths does not fully stabilize all joints of the finger -- because each joint is free to rotate if the other two counter-rotate -- for practical purposes these two muscles stabilize the location of the finger tip.

REFERENCES

- [1] K. W. Horch, F. J. Clark, and P. R. Burgess, "Awareness of knee joint angle under static conditions," *Journal of Neurophysiology*, vol. 38, pp. 1436-1447, 1975.
- [2] F. J. Clark, K. J. Larwood, M. E. Davis, and K. A. Deffenbacher, "A metric for assessing acuity in positioning joints and limbs," *Experimental Brain Research*, vol. 107, pp. 73-79, 1995.
- [3] F. J. Clark and K. W. Horch, "Kinesthesia," in *Handbook of Perception and Human Performance*, vol. I, K. R. Boff, L. Kaufman, and J. P. Thomas, Eds. New York: John Wiley and Sons, 1986, pp. 13-1 - 13-62.
- [4] F. J. Clark, R. C. Burgess, J. W. Chapin, and W. T. Lipscomb, "Role of intramuscular receptors in the awareness of limb position," *Journal of Neurophysiology*, vol. 54, pp. 1529-1540, 1985.
- [5] K. N. An, E. Y. Chao, W. P. Cooney, and R. L. Linscheid, "Normative model of human hand for biomechanical analysis," *Journal of Biomechanics*, vol. 12, pp. 775-788, 1979.
- [6] J. F. Soechting, "Does position sense at the elbow reflect a sense of elbow joint angle or one of limb orientation?," *Brain Research*, vol. 248, pp. 392-395, 1982.
- [7] A. G. Erdman and G. N. Sandor, *Mechanism Design: Analysis and Synthesis*, vol. 1. Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1984.