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Analyzing Human Fingertip Usage in Dexterous Precision Manipulation: Implications for Robotic Finger Design*

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***Abstract*— Designing robot hands for dexterous precision manipulation involves many complex tradeoffs in order to optimize hand performance. While many studies focus on overall hand kinematics, far fewer consider tradeoffs in the design of the robotic finger surfaces themselves. Our present work uses 3.8 total hours of precision manipulation from 19 participants to look at the fingertip surfaces used while moving a sphere through as much of the feasible position workspace as possible. Fingertip surface use is estimated by measuring the relative orientation changes between a high-resolution 6DOF sensor mounted on the fingernails of the fingers and in the object being manipulated, indicating to what extent the object has been "rolled" onto the sides of the fingers. The results show significant lateral use of the index and middle fingers, and also show that the side surface of the index finger is used much more in two-finger manipulation than three finger manipulation. The lateral fingertip usage suggests that robot finger designs could also benefit from enabling lateral surface use. The lateral middle finger use also suggests that fingers can be effectively used as passive supports to supply forces in directions that may not be actively controlled. We anticipate these results should be useful especially for robotic and prosthetic hand design, but also in other fields such as rehabilitation or haptic interface design.**

I. Introduction

Designing a robotic manipulator to enable versatile precision manipulation can involve many complex tradeoffs. While many works formally study these tradeoffs from the perspective of overall hand kinematics [1] or actuation [2], we hypothesize that the geometry of the fingers themselves can also be of critical importance. For example, using flat finger pads can often increase the stability of grasps relative to a rounded geometry, but it may also prevent the fingers from being used effectively at a wide range of angles.

The present work uses human data from a precision manipulation study to understand how the human stably accomplishes common precision manipulation motions, in terms of the usage of the fingertips. The position of a spherical object (Fig. 1) relative to the fingers during a given trial is used to approximate which part of each finger is being used. Overall fingertip usage can then be used to inspire the design of robotic fingers which have similar capabilities. Our method does not require instrumenting the fingertip surface itself, which is important for maintaining natural manipulation motions. The work is particularly relevant for anthropomorphic and prosthetic hands, which may be constrained to have an overall design similar to the human hand, but should give some insights for more general hand design. The results can also be applied in some related domains, such as haptic interface design.

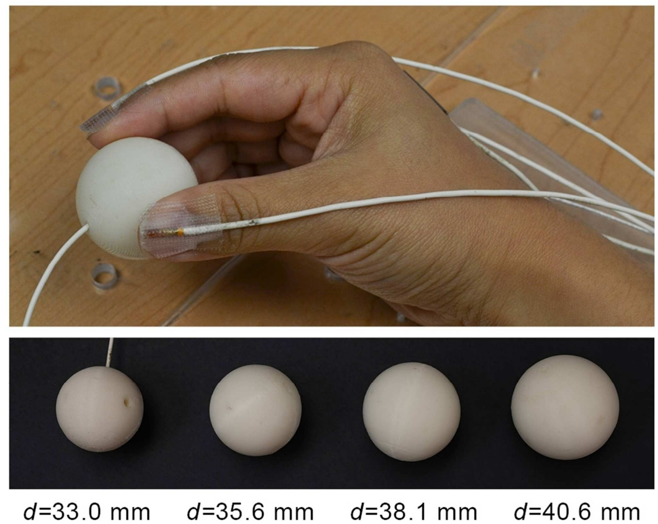

Figure 1. Experimental hand posture, and spherical objects used for manipulation in the study. Target object diameter was scaled linearly based on the participant's hand length. The smallest object has the sensor inserted into the object and the hole for the set screw to fix the sensor in place is visible.

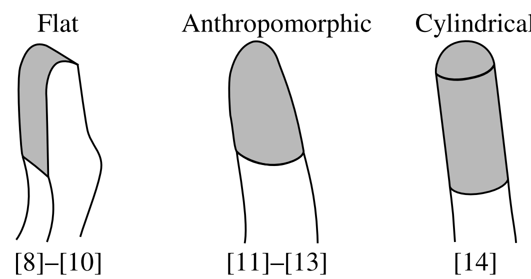

Figure 2. Overview of three common robotic fingertip designs. Reference numbers for example robotic hand implementations are provided.

II. Background

Our work differs from existing work in that it tries to determine experimentally the angular ranges between the fingertip and object during manipulation. Relevant literature will be discussed below.

Replicating the human hand functionality has long been a goal in robotic research. Researchers have tried, for example, to replicate the softness and elasticity [3], [4] of a human fingertip as well as even fingernail and central bone structure

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[5]. Furthermore, models were developed to describe soft fingers during grasping and manipulation [6], [7].

In terms of the shape of the fingertips, it seems the intuition of the creators usually defines how the fingertip is shaped. As shown in Fig. 2, some hands have a flat fingertip, where only the flat surface is designed to interact with the object, such as the SDM hand [8], the Barrett hand [9], and the Schunk Dextrous Hand [10]. A different approach is to shape the surfaces in an anthropomorphic fashion, where the fingertip is round and allows for more flexible manipulation [11]–[13]. Finally, some hands have more generic round surfaces in cylindrical and spherical shapes [14]. However, there is little information on how the finger should be shaped in order to facilitate manipulation. In particular, there is a lack of studies on what finger surfaces are actually used during manipulation. This is likely due to the difficulty of effectively instrumenting the contact surfaces of the finger pads. The present work uses a kinematic approach to approximate the finger surfaces used without having to instrument the finger pad directly, which could disrupt natural manipulation behavior.

There has been considerable effort to classify and describe the manipulative movements of human and robotic hands [15], [16]. Most of those however remain theoretical frameworks and there is very limited information about actual human precision manipulation movements. A previous work used results from another part of the human subjects experiment discussed here to look at overall workspace volumes of a precision manipulation task for haptic device design [17]. In the domain of robotic hands, there has been a lot of effort to describe certain in hand manipulation motions via mathematical frameworks [18]–[20]. However, they have generally not been applied to the human hand.

Kamakura et al. [21] used objects colored with ink to determine the contact area of the hand and object during grasping trials. They used the contact patterns, among other criteria, to create a taxonomy of human grasp types. In the photos it appears that all of fingertip surfaces are used in different grasp types. However, those contact areas are only analyzed qualitatively and likely differ for manipulation movements. Kand and Ikeuchi [22] use the so called "contact web", a discrete description of which finger segments are in contact with the object, to classify grasp types. However, they used a coarse description of contacts over the whole hand surface, and again cannot easily be applied to manipulation movements.

III. Methods

Unimpaired human participants manipulate a spherical object held between the thumb and index finger, or thumb, index and middle finger, while the fingertip and object positions and rotations are measured relative to a hand base frame. A magnetic tracking system records positions while the subject explores their available Cartesian workspace with feedback from a visual display.

A. Participants

19 participants completed the experiment, with 6 male and 13 female, age 18-31 (median 25). Participants were recruited

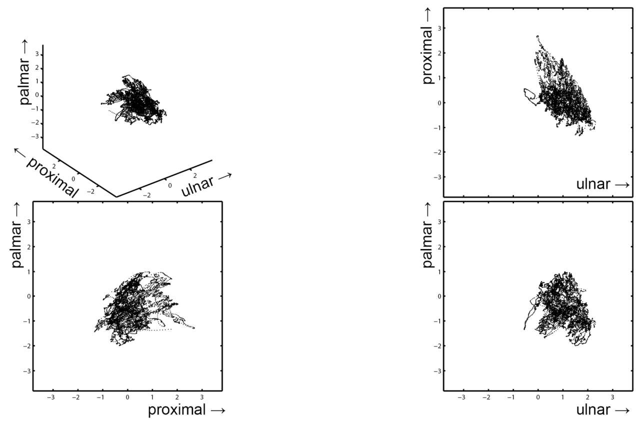

Figure 3. The four specific workspace projections presented to the participants for visual feedback. During the experiment, the axes and axis labels were not shown to avoid distracting the participants.

from the local New Haven community; most are graduate students. Median hand length was 17.5 cm, with a full range from 15.5 to 19.8 cm. All participants were right handed and of normal hand function. The study was approved by the local IRB.

B. Equipment

A magnetic tracking system (trakSTAR, Ascension Technologies, Burlington, VT) was used with eight 2 mm diameter by 1 cm length cylindrical sensors (model 180) to record the main data used in the study. The sensors can be seen attached to the fingertips in Fig. 1. The system provides 6 DOF data at the recommended and used 80 Hz sampling rate. Positional accuracy is 1.4 mm RMS and the angular accuracy is 0.5° RMS. Note that while this and other error sources exist, we believe that analyzing the variability of the results across many participants provides an appropriate conservative estimate for the overall error (see Section IV).

The objects used are four sizes of spheres. 3D printed fabrication was used due to the difficulty of buying premade spheres in small diameter increments. The spheres have diameters of 33.0, 35.6, 38.1, or 40.6 mm, scaled linearly by participant hand length. Sphere masses are 17.8 g, 22.2 g, 27.4 g, and 33.1 g. Post-print sphere diameter accuracy was measured to be within about ±0.25 mm. The spheres have one 2 mm diameter hole for sensor mounting, and another 3.5 mm diameter hole for a nylon setscrew to hold the sensor in place. The best match was chosen to a target diameter specified by $d = 0.2 l_h$, where d is object diameter and l_h is hand length measured from the tip of the middle finger to the palmar wrist crease, both in cm. The scaling factor was selected based on anthropomorphic data in [23] to allow object scaling from a 1% female hand to a 99% male hand. Informal tests showed this to be a comfortable object size that should enable a wide variety of manipulation motions.

Visual feedback of the current manipulation workspace explored is provided using a 27" LCD monitor placed 1 m in front of the experimental table. This visual feedback is designed to help participants explore as much of their position workspace as possible. A diagram of the views used is shown in Fig. 3. One perspective view was used, along with three views aligned with planes defined by two anatomical axes of the hand (distal-proximal, radial-ulnar, dorsal-palmar).

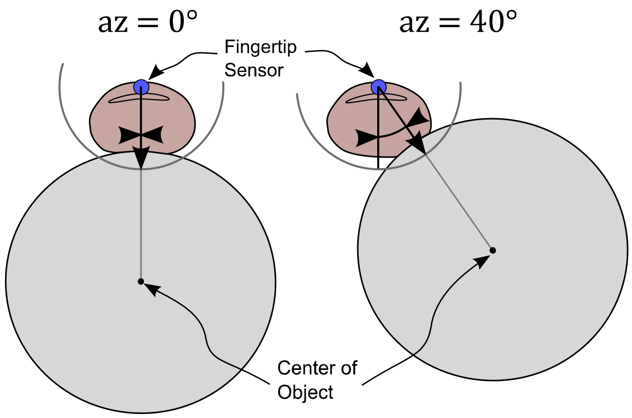

Figure 4. The figure shows the calculation of the fingertip-object angle. This view only shows one angle, whereas the actual calculation calculates both azimuth (az) and elevation (el).

During each trial, participants were instructed both to trace out as much workspace as possible, and also to fill in that workspace volume as best they can. More specific goal-driven feedback methods were decided against due to the high risk of biasing results by the specific characteristics of the goals, rather than capturing natural hand movements.

C. Procedure

Some preparation was performed before the experiment. First, the participants removed metal objects from their person, since metal could distort the magnetic fields emitted by the magnetic tracking system. Then, the participants were shown a short series of slides explaining the experimental procedure. Participants were instructed to trace out as much of their positional workspace as possible and to fill in the workspace as well. They were told to use only the distal finger pad of each finger, up to the first flexion crease from the fingertip. They were also told to minimize sliding of the object, and to avoid removing any fingers from the object during a trial. The participant is thus prevented from using sliding or finger gaiting during the trials. Although this constraint was participant enforced, the experimenter did also observe the participants to make sure they had understood the instructions and were not violating the constraints.

Sensors were then attached to the subject, as can be seen in Fig. 1. 3M Transpore™ tape was used to attach four sensors to the fingernails and wrist. Three more sensors were inserted into 1.5x1.5x0.3 cm rubber mounts and attached to the back of the hand using Top Stick® Men's Grooming Tape. The final sensor was placed inside the object and held in place with a nylon set screw. The sensor cords were draped over the participant's shoulders, and a hook and loop strap was wrapped around the sensors and participant's forearm to provide effective strain relief. The participant was instructed to flex their fingers fully while setting the sensor rest lengths to avoid any tugging of the sensors during the study. Hand length and width were measured according to [23]. The hand position for the trials can be seen in Fig. 1. A plastic guide was used to help the participant keep their wrist approximately straight and their hand in the same location for each trial, while avoiding the constraints on hand motion that other bracing methods could impose. This guide reduces hand

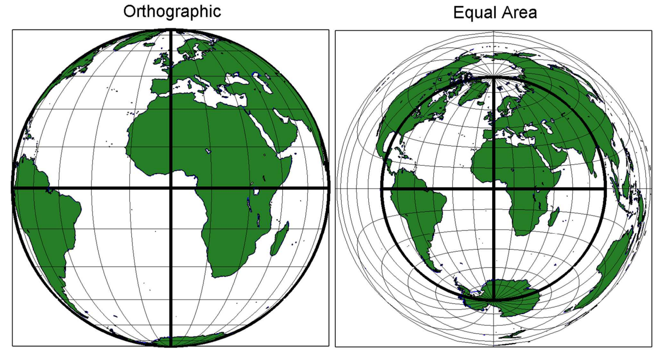

Figure 5. Effect of equal area projection used, compared to orthographic projection. Note that the dark circle indicates the boundary of a hemisphere. The Lambert azimuthal equal area projection is used in the following plots to preserve the density of data points to be able to interpret scatter plot density appropriately.

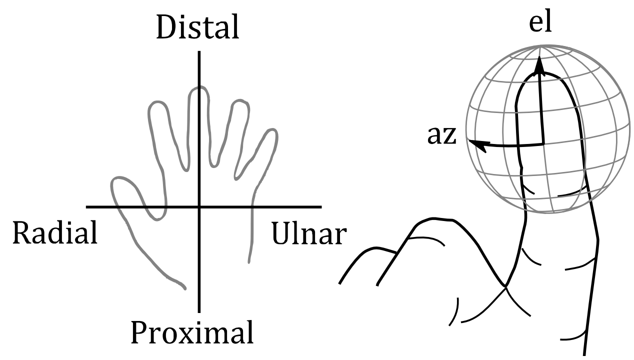

Figure 6. Major anatomical directions of the right hand, as well as the spherical coordinate system of the fingertip contact points. Elevation (el) is positive in direction towards the fingertip, whereas azimuth (az) is positive in ulnar direction.

base frame movements due to skin motion and keeps the direction of the gravity vector constant.

For this work, two blocks of trials involving the spherical object (Fig. 1) manipulated with two and three fingers will be considered. The full study did include additional trials with a pointed object and individual finger movements. These additional trial types are noted simply to give a full understanding of the set of tasks each participant had to perform during their experimental session, and some of the results from the pointed object trials can be seen in [17]. The order of the trial blocks was randomized. Before each block of three trials, a one minute practice period was given for the participant to explore the workspace without visual feedback. Following the practice, three two-minute workspace trials were performed. Before every trial, the hand was placed in a calibration fixture to re-calibrate the sensor orientations. After every trial, a rest period of about 30 s was given. In total, the duration of the trials was about 80 minutes, including the time required for the experimenter to switch between trial conditions.

D. Fingertip Usage Analysis

The usage of the fingertips is analyzed by projecting the positions of the spherical object into a local finger coordinate frame defined by the fingertip sensor attached to the center of the participant's fingernail. These vectors are then normalized and plotted on the surface of a sphere, as shown in Fig. 4. By seeing where the object is relative to the fingertip throughout the trials, we can understand which overall

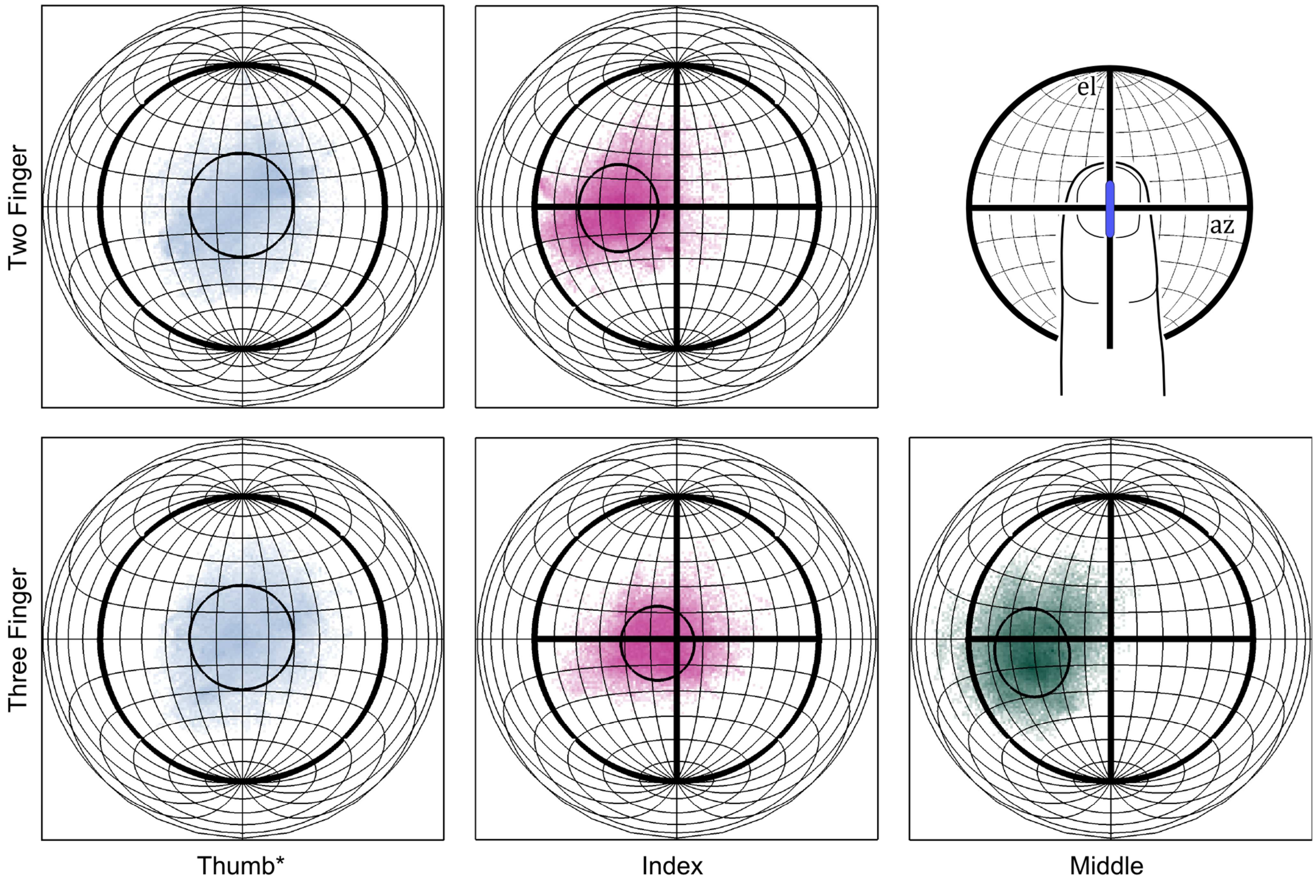

Figure 7. Overview of finger usage. An equal-area projection is used to preserve apparent density of points. Shape distortion is fairly minimal for the data plotted. The top - right plot shows how the projection relates to the finger. The origin of the plot is the finger sensor (indicated by blue cylinder). The small circle corresponds to the cone size that includes 68% of the data. Note that this cone does not indicate the uncertainty of the mean, which would be much smaller. The bold crosshair and large circle correspond to the hemisphere as illustrated in Fig. 5. *The absolute thumb orientation is unknown, therefore the coordinate axes were removed and only the spread of the points is relevant.

surfaces of the finger are most important and frequently used in precision manipulation.

Proper choice of coordinates and projections help to analyze the data effectively without producing misleading graphics or results. The Lambert azimuthal equal-area projection is used to present scatter plots in order to preserve the visual density of the points, as recommended in [24]. The effects of the projection can be seen for the world map in Fig. 5. Note that there is also little shape distortion for half of the sphere, where most of our data lies.

For specifying positions on the unit sphere, we will use azimuth and elevation angles [25], as shown in Fig. 6, which are equivalent to the familiar longitude and latitude angles used in geographic coordinates. The azimuth and elevation angles can be mapped to spherical coordinates by: $\theta = 90 - el$, $\phi = -az$. The *mean direction* or center of the point cloud on the sphere can be found by normalizing a simple Cartesian vector sum, which corresponds intuitively to the center of mass of the points, if each point on the sphere is defined to have unit mass. It is also useful to have a good measure of dispersion of the points. Distributions such as the rotationally symmetric Fisher distribution and elliptical Kent distribution can be used to model the distribution of a cloud of points [24]. Although each of these parameters does have a dispersion parameter somewhat similar to variance or standard deviation, the values are not easy to intuitively understand or relate back to more conventional statistical approaches.

To understand the dispersion of the data, we will instead use distribution-free approaches which can be connected more intuitively to conventional statistical methods. We define a *68% cone* and a *95% cone* by symmetrically expanding a cone with its axis at the mean orientation of the data until the cone encompasses 68% or 95% of the data points, respectively. The angles for these cones can then be discussed as a measure of point dispersion interpreted similarly to a one or two standard deviation range. Note that while there are multiple possible cones that contain a given percentage of points, there is only one unique cone centered at the mean of the points. The circles corresponding to the intersection of these cones with the spherical surface are plotted in Fig. 7 and 8. Note that in the following discussion we will specify the full cone angle rather than the semi-vertical angle.

To assess the significance of angular shifts between different fingers and conditions, we took the means from the individual participant data (Fig. 8) and used a paired t-test to assess whether azimuthal and elevation angular shifts are significant. All p-values reported below are from this method. Uncertainties with ± notation which follow denote 95% confidence intervals calculated by standard deviation. Analyzing the resulting means directly across many

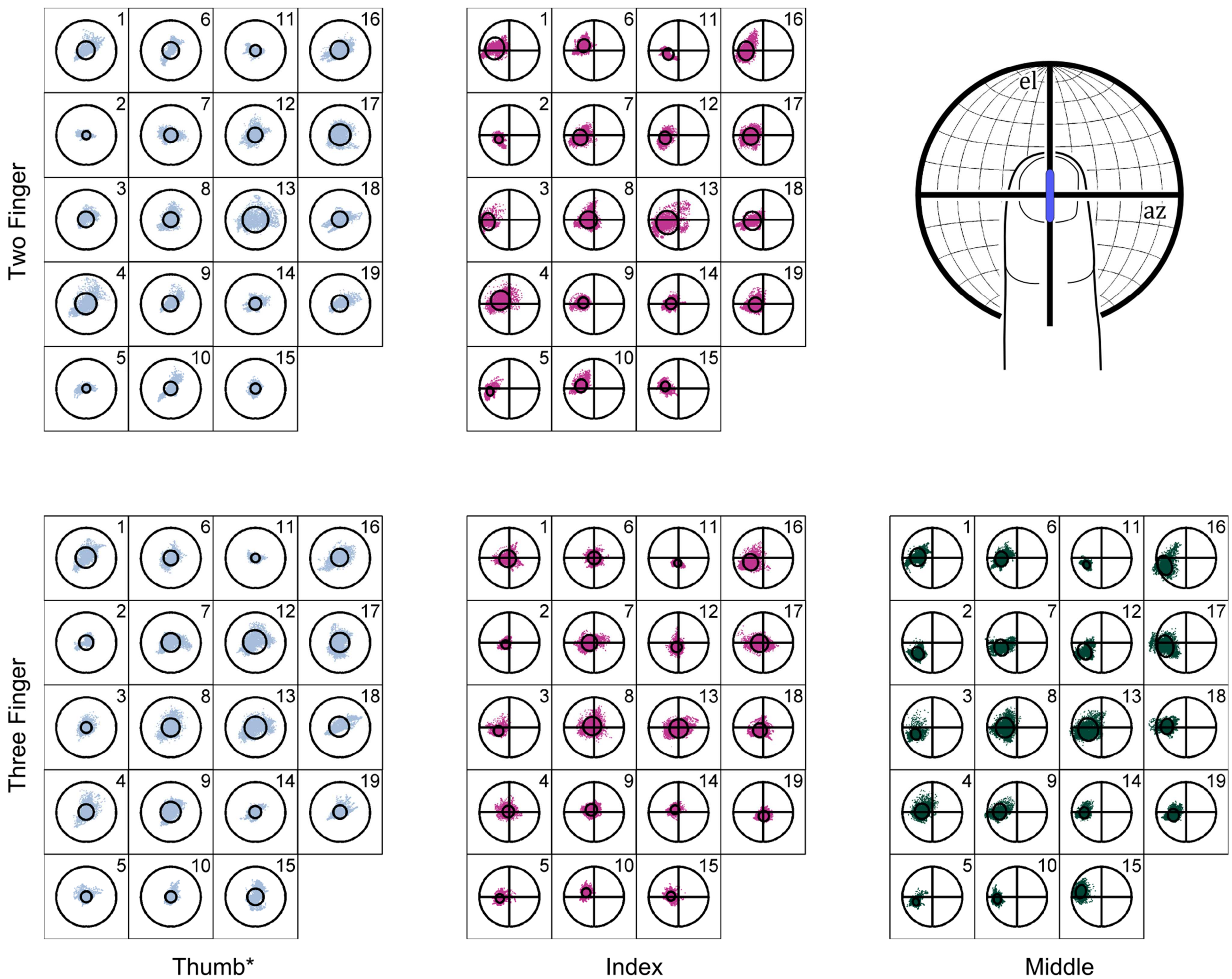

Fig. 8. Finger usage by participant. An equal-area projection is used to preserve apparent density of points. The upper right plot shows how the projection relates to the finger, as in Fig. 6. The small circles correspond to the cone size that includes 68 % of the data. The crosshair and large circle correspond to the hemisphere as illustrated in Fig. 5. *The absolute thumb orientation is unknown, therefore the coordinate axes were removed and only the spread of the points is relevant.

participants in this way should provide a conservative estimate of any non-systematic errors present.

IV. Results

Before analyzing the main results, we will first assess the overall uncertainty of the data. The calibration position data taken before each trial indicates how accurately we can estimate the coordinate frame orientation at each fingertip. The alignment of the index finger is most consistent, with mean deviation from perfect alignment of 7° and a 68% cone of 7°. The middle finger data is also quite reliable, with 10° of mean deviation relative to the index finger, and a 68% cone of 9°. These small angular ranges show good performance of the calibration fixture. Because the thumb, unlike the index and middle fingers, was not resting flat against a controlled surface in the calibration posture, we cannot confidently determine the orientation of the thumb frame – thus for the thumb we will look only at the angular ranges for the trials, which are still just as accurate as for the other fingers.

The combined data for all participants is shown in Fig. 7. For the thumb, absolute orientation data is not available, but the range of thumb surface used is similar between the two and three finger conditions, the 68% cones are 29° for 2 fingers and 30° for 3 fingers, and the 95% cones are 45° for both conditions. The index finger results show a large shift of 23±4° in azimuthal angle between the two and three finger cases ($p<.001$), showing that the index finger lateral surface on the radial side is used much more during the two finger trials. The spread of angles is slightly smaller in the three finger case – the 68% cones are 24° and 21° for the two and three finger cases, respectively, while the respective 95% cones are 41° and 36°.

The middle finger shows even more use of the side of the finger, with the overall distribution mean at $(az, el) = (-47°, -7°)$. This middle finger mean is shifted azimuthally from the index finger, 3-finger trial mean by -36±4° ($p<.001$), and from the index finger, 2-finger trial mean by -12±5° ($p<.001$). The spread of angles is similar to the index finger, with 68% and 95% cone angles of 23° and 40°, respectively.

Smaller shifts in the distal-proximal direction (elevation angle) were observed for the means between different experimental conditions or fingers. The index finger locations used in the two-finger manipulation condition are shifted distally by 6±3° (*p=.001*) in elevation angle relative to the middle finger distribution. The index locations in the three-finger case are likewise shifted distally by 5±4° (*p=.02*) relative to the middle finger case. There is no significant distal-proximal shift between the two and three-finger index finger distributions (*p=.28*)

Because of the large variability in manipulation strategies used between participants, it is useful to also look at the individual participant results, shown in Fig. 8. The range of thumb angles observed varies quite a bit in both the two and three finger cases. For example, in the three finger case, participant 2 has a 20° 95% cone, while participant 13 has a 56° cone.

For the index finger, the lateral shift of the data in the two fingered trials is still evident visually from the individual participant data. There do not seem to be any participants at all who have the mean angle at the center of the finger pad. Some participants such as 4 and 13 manage to use the ulnar side of the index finger in the two fingered trials, but this is rare. For the three fingered trials, on the other hand, almost all participants use the ulnar side of the finger pad at least some. Many participants are fairly balanced in radial and ulnar surface use when using three fingers, while a few such as 5 and 15 still have a slight bias in the radial direction.

Finally, the middle finger is used extensively on its radial side by all participants. Some variability can be noted in the distal-proximal direction (elevation angle). For example, participant 2 has a proximally biased mean at $(az, el) = (-44°, -28°)$, while participant 15's mean is a full 40° more distal at $(-61°, 12°)$. This amount of distal-proximal variation appears to be greater than for the index finger.

V. Discussion

Overall, the results show important aspects of how the fingertips are used during precision manipulation, which can be used as inspiration for the design of robotic manipulators which draw on similar strategies.

The thumb is shown to be used over a slightly larger angular range than the other fingers. For robotic hand design, one might hypothesize that if a finger is suitably dexterous, it might be adequate to have a simpler finger surface, such as a flat surface, which only allows manipulation in a small range of angles. However, the large angular range observed in the thumb data suggests that even very dexterous digits can still benefit from using a wide range of finger surface.

The index finger usage highlights how the optimal portion of the finger surface depends on the overall grasp used. In the two finger case, the ulnar side of the finger is used very rarely, with a heavy emphasis on the radial side. While it is possible to use the ulnar side of index finger while rolling a sphere with two fingers, it may require using the side or even back of the thumb. Thus, it is likely either that this motion was unintuitive to the participants, or that they would have performed this rolling motion more if active exploration of the orientation workspace was also emphasized. Overall, it is clear that the side surface of the index finger is used frequently, especially during two finger manipulation.

The shift in index finger usage between the two finger cases also shows that the role of the middle finger is significant, since if the middle finger played a minor role, we might expect little difference in the surface used. This is consistent with the grasping study of [26], which showed that the thumb opposes roughly an average of the other finger contact positions, rather than having a single dominant finger oppose the thumb directly. Adding the middle finger allows a different part of the index finger surface to be used, suggesting that by using two fingered manipulation in some cases and three-fingered manipulation in others, an overall larger manipulation workspace may be possible.

The main part of the middle fingertip used is even further to the side, with some points even past 90°. This suggests that the middle finger is frequently applying forces in a direction that is not actively controlled. Instead, the passive stiffness of the finger is being used to support the object. This gives some inspiration for similar robotic strategies, where a finger could be used as a sort of movable endstop to help passively support the object. In multi-finger manipulation, it may sometimes improve grasp stability for some of the fingers to be relatively rigid, rather than trying to control all fingers actively.

It is worth noting that the hand positions observed were implicitly required to be fairly stable. The participants needed to actively manipulate the spheres for a full two minutes without dropping the object or making adjustments with the other hand and fingers. Several participants did drop the object, in which case the trial was repeated. Although this does mean that some extreme possible postures were likely not captured, it also means that the positions observed are reasonably stable. This makes the data better for inspiring robot hand design, since a robot hand that is dexterous but with poor grasp stability would be impractical for most applications.

VI. Conclusions and Future Work

Overall, the human fingertip usage data discussed should provide inspiration for designing robotic fingers for dexterous manipulation. The data show that both the index and middle fingers are used extensively on their lateral surfaces, suggesting that stable grasping properties on the side surfaces of robotic fingers should not be neglected. The index finger data shows the grasp configuration influences the most practical range of fingertip surface to use. The usage of the more lateral surface of the middle finger highlights that passive finger stiffness can be used effectively in multi-finger grasps, even when the finger cannot be actively controlled in the direction it is applying force. While using the side of the finger appears to be important in human precision manipulation, it is worth noting that designing the entire 360° surface for grasping may be unnecessary – it seems a contact angle range of 90° to 180° should suffice for any of the motions observed. The requirements of the task do ensure that the data presented is for relatively stable parts of the hand workspace, suggesting that similar strategies could be used to achieve stable grasps in robotic grippers.

While the present work already conveys useful information about finger usage in precision manipulation, we also envision ways in which the present work could be expanded or investigated in more detail. A future study could clarify more details of thumb usage through carefully applying additional calibration procedures. Other object shapes or sizes could be studied. The task used for the current study did focus on versatile exploration of the Cartesian workspace, so a study focusing on rotational motions may produce somewhat different results. Future work could also consider finger gaiting [15] motions, which were not allowed in the current study. Overall, we hope the current work will help inform the development of robotic hands which can implement human-like precision manipulation strategies. The results may also be applicable in other domains related to human precision manipulation, such as haptic interface design or the design of tools for fine manipulation.

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