Human Precision Manipulation Workspace: Effects of Object Size and Number of Fingers Used

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***Abstract*— Precision manipulation, or moving small objects in the fingertips, is important for daily tasks such as writing and key insertion, as well as medically relevant tasks such as scalpel cuts and surgical teleoperation. While fingertip force coordination has been studied in some detail, few previous works have experimentally studied the kinematics of human precision manipulation with real objects. The present work focuses on studying the effects of varying object size and the number of fingers used on the resulting manipulation workspace, or range of motions that the object can be moved through. To study object size effects, seven bar-shaped objects ranging from 20 to 80 mm length were tested; after scaling object length to the equivalent for a 17.5 cm hand, the peak volume was obtained for 48-59 mm object length range (23% above average), and the minimum volume was obtained for the smallest 17-27 mm range (72% of average). 50 mm and 80 mm circular objects were used to study the effect of using different numbers of fingers; the five-finger manipulation volume dropped to less than half the two-finger volume (*p<0.001*). We anticipate these results will be useful in designing devices such as hand held tools, as well as in designing protocols for effectively testing and rehabilitating hand function. Finally, the results can provide a benchmark for the manipulation capability of prosthetic hands.**

I. Introduction

Precision manipulation, which we define as repositioning small objects in the fingertips, is used extensively in activities of daily living such as writing and inserting keys and electronic device connectors. It is also used for small tools, such as tweezers, screwdrivers, soldering irons, or scalpels. In the medical domain, one important use of precision manipulation is for surgical teleoperation systems (e.g. [1]).

The present work focuses on understanding how *precision manipulation workspace* is affected by the object size and number of fingers used for manipulation. We define this workspace as the range of motions through with a person can feasibly move an object held in the fingertips (see Fig. 1), without removing any fingers or sliding the fingertips along the object. The volume of this workspace is simply the volume of a 3D shape constructed to include all of the points the object moves through – in this case we use voxels to construct this 3D shape, as discussed in Section III.E.

Better understanding precision manipulation workspace can be useful in a variety of domains. Precision tools such as surgical tools or teleoperation devices can be designed to maximize the ability of the hand to dexterously move the tool in the fingertips. In the area of hand function testing and rehabilitation, the current work can be used both as a reference point for healthy hand capability, and also to better choose which objects and finger conditions should be used for testing and rehabilitation. Finally, the workspace results can be used to benchmark the capabilities of a prosthetic hand.

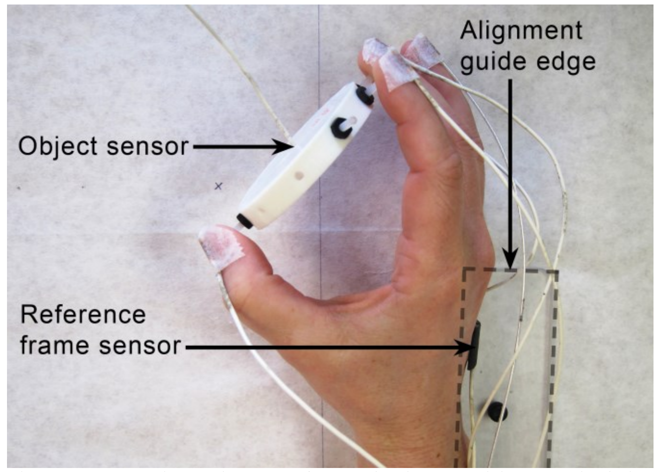

Figure 1. Experimental setup for evaluating precision manipulation workspace. Motions of the object, as measured by the object sensor, are referenced relative to a sensor affixed to back of the hand, along the 4th metacarpal. A slightly raised alignment guide provides an edge for the participant to align the back of their arm and hand against. Additional sensors were attached to the fingertips, but the finger positions are not used in the current work.

II. Background

Few existing works experimentally study within-hand kinematic workspace of human precision manipulation for a non-zero size object. Previous work from the authors has analyzed overall workspace shape and size for two or three fingers [2], but has not considered multiple object sizes, or the effect of using four and five fingers during manipulation. It should be noted that the existing literature studying fingertip forces, such as to better understand motor control, is much more extensive than the kinematic approach taken in this work – for a review of the force-centric approach see [3].

Some previous work has analyzed pinch grips or fingertip manipulation, but not directly with a non-zero size object. Previous work has examined *functional workspace* by calculating the intersection of individual finger trajectories to estimate available precision pinch range of motion [4], [5]. However this work effectively assumes a zero-size object. Youm et al. [6] modeled a workspace using a similar method, producing a planar model for a 3-fingered grasp. Yokogawa

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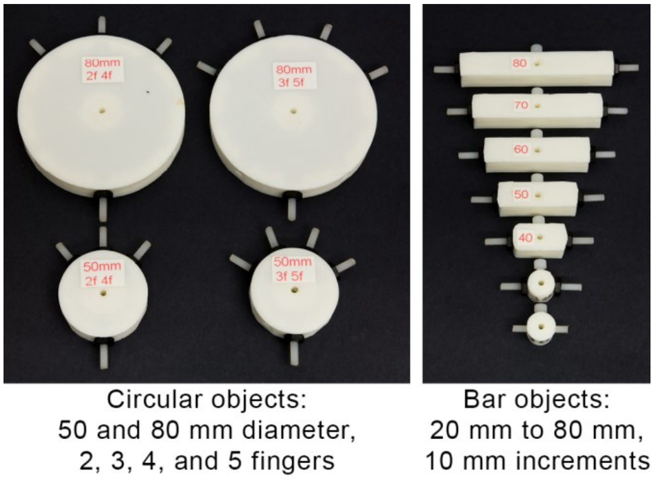

Figure 2. Objects used in the study. The circular objects were used to study the effect of changing the number of fingers used with two different sizes, and use 40° spacing of the finger contacts. Seven sizes of bar-shaped objects are used to study the effects of object size. All object lengths and diameters are expressed including the length of the 4-40 nylon screws which were used for the finger contact points.

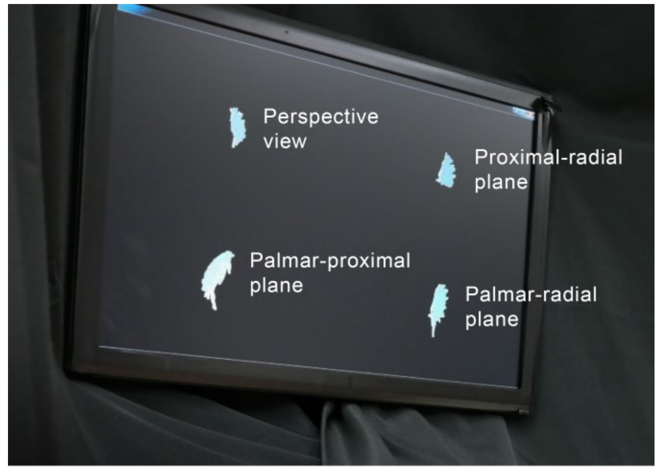

Figure 3. Visual feedback setup. A 27" monitor 1 m in front of the experimental table is used for feedback. The object workspace explored is shown to the participants in four different views – in three planes aligned with the hand axes, and one perspective view. (The text labels are shown here for explanatory purposes – no text was displayed during the study.)

et al. study the manipulability of the thumb and index finger in three discrete postures in [7].

Various robotic works (e.g. [8]–[11]) have analyzed precision manipulation for robotic hands, using approaches such as parallel platform methodology or linkage systems. However, these works have not analyzed precision manipulation in the specific human hand case. Overall, the existing works have addressed fingertip force coordination, and some of the kinematics for manipulation of a zero-size object, or provided general frameworks for analysis, but existing works have not experimentally addressed the effects of object size and number of fingers on precision manipulation workspace.

III. Methods

Unimpaired human participants used their fingertips to manipulate two classes of objects (Fig. 2), a bar-shaped object of 7 different lengths, and two sizes of circular objects. The bar object is used to study object length effects, while the circular object is used to study the effect of using 2, 3, 4, and 5 fingers. If the standard numbering of the thumb, index, middle, ring, and little fingers as fingers 1, 2, 3, 4, and 5 respectively is used, then the n-finger case involves using fingers 1 through n. For example, the two-finger case involves using fingers 1 to 2, or the thumb and index finger. A magnetic tracker sensor in the object records workspace points relative to a reference frame sensor on the back of the participant's hand. The study was approved by the Yale University IRB, and all participants were individually consented and financially compensated for participation.

A. Participants

16 participants (11 female, 5 male) from the local university and city community completed the experiment. Participants were aged 22 to 41 (median 26). Hand length, measured from wrist crease to middle fingertip, ranged from 15.4 cm to 21.1 cm, with median 17.8. The experimental setup required right-handed participants, and any participants with significant prior hand or wrist injuries were excluded from participation. Members of the authors' research group were also excluded from participation.

B. Equipment

A magnetic tracking system with 1.4 mm RMS positional accuracy and 0.5° RMS angular accuracy was used to measure object position relative to a hand reference frame (trakSTAR system, Ascension Technologies, Burlington VT). A medium range transmitter (MRT) and ruggedized MODEL 180 2mm diameter cylindrical sensors were used. Each sensor provides full 6 DOF data (*x, y,* and *z* position and rotation matrix). One sensor is fixed in the object using a nylon setscrew, and a reference frame sensor is placed in a small rubber sleeve and adhered to the back of the hand (along the 4th metacarpal) using Top Stick® Men's Grooming Tape.

The two types of objects used are shown in Fig. 2. The bar-shaped object lengths (including screw length) are in 10 mm increments from 20 mm to 80 mm, and their corresponding masses are 0.5, 0.9, 1.4, 2.1, 2.5, 3.1, and 3.5 grams. The circular objects, including screw length, are either 50 mm or 80 mm diameter. The contact points are at 40° spacing for the fingers, matching the natural finger spacing observed in [12]. For each object diameter, an "odd" (3 and 5 finger) and "even" (2 and 4 finger) object variant are used, to ensure that the fingers still directly oppose the thumb regardless of the number of fingers used. The 50 mm object weighs 4.1 g for the 2 and 4 finger version and 4.3 g for the 3 and 5 finger version. The 80 mm object weighs 8.9 g for the 2 and 4 finger version, and 9.2 g for the 3 and 5 finger version. All objects use 4-40 nylon screws for the finger contact points, with 2.6 mm outer diameter. Objects are entirely plastic to prevent any interference with the magnetic tracker measurements.

A 27-inch (68.5 cm diagonal) LCD monitor 1 m in front of the experimental table provides visual feedback to participants, as shown in Fig. 3. This screen displays the 3D object workspace in three views of planes aligned with the anatomical hand axes, as well as one perspective view.

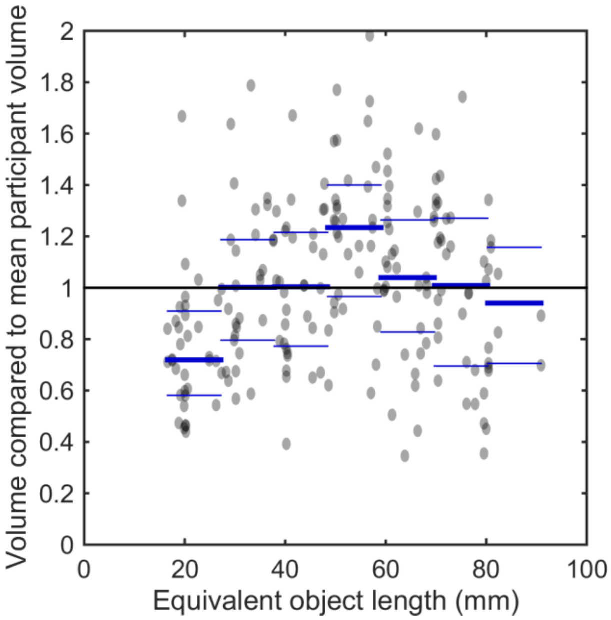

Figure 4. Volume vs. object length relationship. The blue bars show 25th percentile, median, and 75th percentile for the data. A trend with peak volume for a mid-range object size, and reduced workspace for the smallest and largest objects is suggested. The largest volume difference occurs between the smallest and middle size objects.

C. Procedure

Participants completed two two-hour experimental sessions on separate days. A separate session is used for the bar objects (varying length) and the circular objects (varying number of fingers). Session order is randomized. Separate days were used for the sessions to reduce hand fatigue. For the bar object session, participants complete two 2-minute trial blocks for each object length, for 14 total trials. For the circular object, 2 object sizes (50 mm and 80 mm diameter) and 4 finger conditions (2, 3, 4, and 5 fingers) are used with two trials each, for 16 trials total. The order of each block of two trials is randomized. Participants are instructed to move the object in the fingertips and trace out as much area as possible on the monitor, thus exploring their manipulation workspace. During the trials, participants rest their hand on a flat surface, with the back of their arm and hand straightened against an alignment guide edge raised 6 mm above the table surface (see Fig. 1). They are instructed to minimize wrist movement, but small wrist movements are permissible since all object motions are referenced relative to a base sensor on the back of the hand. Trials in which the object is dropped (7 % of trials) are removed from the data for final analysis. These occasional drops show that maintaining stable object contact for a full two minute trial without external adjustments can be difficult.

D. Data Normalization

We anticipate that most effects of interest will scale with the size of the hand. For example, we expect that the size of the object relative to the size of the hand will better define how it is manipulated than the absolute size of the object. Thus, we have normalized all lengths based on the measured length of

TABLE I. VOLUME VS. OBJECT SIZE RELATIONSHIP

Bin center (mm)	21.9	32.5	43.1	53.7	64.4	75.0	85.6
25th percentile	0.58	0.80	0.77	0.97	0.83	0.70	0.71
Median	0.72	1.00	1.00	1.23	1.04	1.01	0.94
75th percentile	0.91	1.19	1.22	1.40	1.26	1.27	1.16

each participant's hand. The individual workspace points for a given participant i are scaled according to

$$(x', y', z') = \left(\frac{\bar{l}}{l_i}x, \frac{\bar{l}}{l_i}y, \frac{\bar{l}}{l_i}z\right), \tag{1}$$

where $\bar{l}$ is the reference hand length, l_i is the given participant's hand length, and the primed coordinate frame is the scaled data, relative to the unprimed frame's raw data directly from the sensor measurements. Scaling to fit a reference hand length helps to keep measurements more intuitive, compared to unitless normalization methods. In this case, we use 17.5 cm as the reference hand length for consistency, because it was the median hand length scaled to in our previous related study [2]. It is also close to the median hand length from this study's participants (17.8 cm).

When considering object diameter (circular object), or object length (bar object), an *equivalent object length* (or diameter) is calculated using the same scaling relationship. Specifically,

$$l'_{object} = \frac{\bar{l}}{l_i} l_{object}, \tag{2}$$

where the equivalent object length l'_{object} is scaled to the equivalent length for the reference length ($\bar{l}$) hand, based on the hand length (l_i) for each participant.

E. Volume Calculation

Following the scaling of the object workspace data as described in Section III.D, workspace volumes are calculated using a voxel binning method, as in [2]. Specifically, the object workspace points are binned into a three dimensional grid of voxels with 2.15 mm length for each edge of the voxel cube, the edge length used in [2] is maintained.

IV. RESULTS

A few initial effects were evaluated before testing the main effects of the object size and number of fingers used. After scaling the data for hand size, a moderate sex effect is present, with female participants producing 14 % larger workspace volumes on average than the male participants, with a two-tailed t-test giving $p = 0.02$. (Prior to data scaling, the male workspace volumes are actually 26 % larger, presumably due to larger average hand size). An experience effect was checked for, to see if average volume increased over the course of both experimental sessions. If a linear regression model is applied, the predicted increase in volume is 0.77 % per trial, up to a total of 23% over the course of all 30 trials ($p = 0.04$).

A. Effects of Object Size

The effects of varying object length on workspace volume are shown in Fig. 4 and Table 1 for the bar object. Equivalent

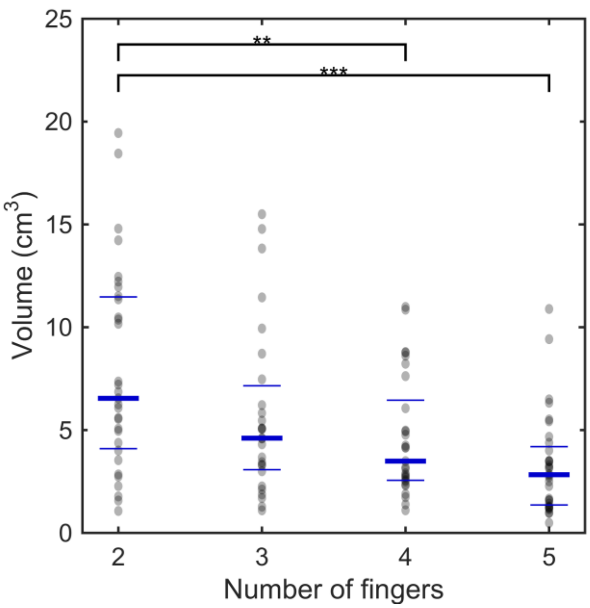

Figure 5. 50 mm circular object, volume vs. number of fingers. Statistically significant reductions in volume are present for 2 vs. 4 or 5 fingers. ** denotes *p<0.01* and *** denotes *p<0.001*. The blue bars show 25th percentile, median, and 75th percentile for the data.

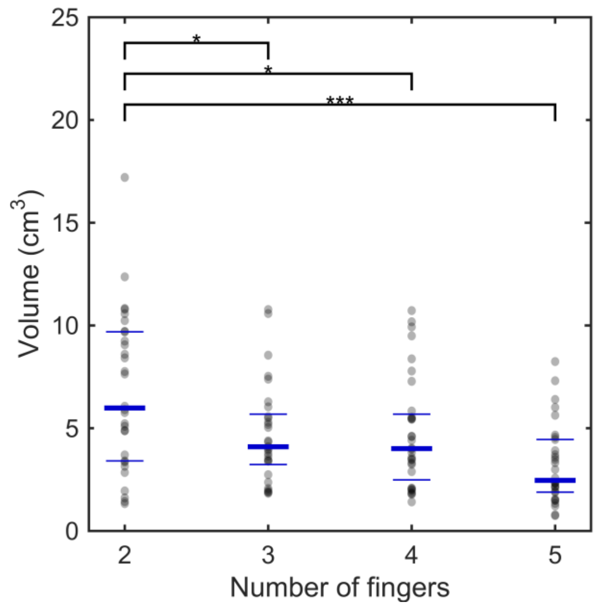

Figure 6. 80 mm circular object, volume vs. number of fingers. Significant reductions in volume occur between 2 fingers and 3, 4, and 5 fingers. * denotes *p<0.05*, and *** denotes *p<0.001*. The blue bars show 25th percentile, median, and 75th percentile for the data.

TABLE II. VOLUME VS. NUMBER OF FINGERS

Number of fingers used	**50 mm circle volume (cm^3)**			**80 mm circle volume (cm^3)**		
	25th	***Median***	***75th***	***25th***	***Median***	***75th***
2	4.10	6.54	11.48	3.41	5.98	9.69
3	3.07	4.61	7.15	3.23	4.10	5.68
4	2.56	3.49	6.45	2.49	4.01	5.68
5	1.36	2.83	4.19	1.89	2.46	4.45

"25th" and "75th" indicate the 25th and 75th percentiles of the data, respectively.

object lengths for a 17.5 cm length hand are calculated as described in Section III.D. The volume for each trial is divided by the mean volume for all the successful bar object trials for that participant. For example, if the volume for a particular trial is 1.5, it indicates that that the participant achieved 50% more volume than that participants overall average for all lengths of the bar object.

The equivalent diameters are binned into seven different equally spaced ranges, since seven sizes of physical objects were used. An overall median, 25th percentile, and 75th percentile volume are calculated for all trials within the object diameter range for that bin. These values can be seen through the horizontal lines in Fig. 4, as well as in Table I. The bin width is 10.6 mm to provide seven equally spaced bins across the entire equivalent diameter range. Single factor analysis of variance (ANOVA) was used to test for equal means, giving $p < 0.001$. P-values for pairwise tests of the means were adjusted with a Bonferroni-Holm correction factor [13] for multiple comparisons ($\binom{7}{2} = 21$ comparisons), to give the final corrected p-values discussed below.

The results show a reduced volume for the smallest object size, and suggest an overall trend where the middle size range produces the highest volume, with a drop off in volume on either end. Specifically, the decrease in volume of the smallest (17-27 mm) equivalent length is statistically significant when compared to three other ranges: 27 mm to 38 mm ($p = 0.04$), 48 mm to 59 mm ($p < 0.001$), and 59 mm to 70 mm ($p = 0.01$). The middle-sized 48-59 mm range has a median volume 23% above average, whereas for the smallest 17-27 mm range, the volume is only 72% of average.

B. Effects of Number of Fingers

The effect of varying the number of fingers used on volume for the 50 mm object is shown in Fig. 5, and Fig. 6 shows the same effects for the 80 mm object. The medians are shown in Table II along with the 25th and 75th percentiles for the data. For both cases, a single factor analysis of variance (ANOVA) was first applied, to test whether the number of fingers has an effect on workspace volume. This gives $p < 0.001$ for both the 50 mm and 80 mm objects, so we reject the null hypothesis that the mean volume is the same regardless of number of fingers used. The difference in volume between the 50 mm and 80 mm object cases was not found to be significant if the number of fingers is kept the same.

Following this initial test, a multiple comparison procedure was performed with the same Bonferroni-Holm correction applied to the p-values to test pairwise whether the means are equal. For the 50 mm diameter object, significant differences are present between the two finger case and the four and five finger cases. Specifically, the difference between the two finger and four finger case is significant with $p = 0.006$, and for comparing the two and five finger cases, $p < 0.001$. The median workspace volume for two fingers (6.54 cm^3) is more than double the median volume for the five finger case (2.83 cm^3).

For the 80 mm diameter object, significant decreases in volume are also present when more fingers are used for manipulation. Specifically, the mean of the two-finger volumes is significantly different from the 3, 4, and 5 finger volumes, with $p = 0.03$, $p = 0.03$, and $p < 0.001$ respectively. Again, the median volume for the 2-finger case (5.98 cm^3) is more than double the median volume for the 5-finger case (2.46 cm^3).

V. Discussion

Overall, the object size and number of fingers used has a significant effect on the achievable precision manipulation workspace. A high level of variability is also present, which may result from individual differences in which motions are intuitive, joint motion ranges, and the level of effort.

The object size effects have important implications for device design. In general, the results suggest precision tool handles should have an optimal size range which can help to maximize the precision manipulation workspace. In the medical domain, this could be applied to hand-held surgical tools or haptic interfaces for surgical robots [1], where using within-hand manipulation could improve precision or reduce energy usage. As shown in Fig. 4, the optimal size range found is 48 mm to 59 mm, or 27 % to 34 % of hand length. However, the optimal size for specific devices could be affected by other factors, such as long term user comfort or other points at which the device makes contact with the hand.

The object size vs. workspace volume trend also has implications for hand functional assessment and rehabilitation. Using an object size in the range of 27 % to 34 % of hand length could help participants to comfortably explore a large range of their workspace. Overall, the relatively smooth and subtle volume vs. object size trend suggests that a relatively small number of object sizes may be sufficient both for testing precision manipulation ability, as well as for rehabilitation exercises. However, there may still be significant underlying differences in the finger motions used as object size is changed.

In addition to the object size trends, the current study shows a significant reduction in workspace volume when more fingers are used for precision manipulation of the object. In general, adding a single finger to the object during manipulation does not appear to have a large effect, but going from two to five fingers reduces the average workspace volume by a factor of 2 or more. This reduction is expected due to the additional kinematic constraints that the extra fingers provide. However, adding fingers could also make the manipulation more stable, potentially allowing participants to explore a larger range of motion without risk of dropping the object. These two effects are in opposition, but since the workspace decreases with added fingers, the extra kinematic constraints appear to be the dominant factor.

The workspace reduction as more fingers are used in manipulation has implications both for device design and for rehabilitation. Tools which have grips designed for more fingers may have more stability or allow higher forces [14], but will also sacrifice freedom of movement, especially if 4 or 5 fingers are used. For clinical assessment of precision manipulation function in the hand, the results indicate two-finger trials give the best measure of the maximum workspace that can be achieved. If rehabilitation of precision manipulation function is required, the results highlight some trade-offs in rehabilitation protocols. For example, performing tasks with only two fingers would allow the largest functional range of motion to be explored, but the remaining three fingers will be left untrained.

VI. Conclusion

Overall, the results of this study show a middle range of object sizes which produce a large workspace, a range of small object sizes which produce a small workspace, and a significant reduction in workspace as more fingers are used during manipulation. Future work could include studying specific related real-world tasks of interest, or studying more free-form manipulation where participants are allowed to remove fingers from the object during manipulation. While the observed trends could be affected by different object shapes or task constraints, we anticipate the results will still provide a useful reference point for many applications, including designing devices for precision manipulation, evaluating and rehabilitating precision hand function, or benchmarking the capabilities of a prosthetic hand.

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