Dexterous Workspace of Human Two- and Three-Fingered Precision Manipulation

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ABSTRACT

Precision manipulation, in which an object held between the fingertips is translated and/or rotated with respect to the hand without sliding, is used frequently in everyday tasks such as writing, yet few studies have examined the experimental precision manipulation workspace of the human hand. This study evaluates the range of positions over which 19 participants manipulated a moderately sized (3.3-4.1cm diameter) object using either the thumb and index finger (2 finger condition) or the thumb, index and middle fingers (3 finger condition). The results show that the 2-fingered workspace is on average 40 % larger than the 3-fingered workspace ($p < 0.001$), likely due to added kinematic constraints from an additional finger. Representative precision manipulation workspaces for a median 17.5cm length hand are shown from multiple views to clearly illustrate the overall workspace shape, while the general relationship between hand length and workspace volume is evaluated. This view of the human precision manipulation workspace has various applications, ranging from motivating the design of effective, comfortable haptic interfaces to benchmarking the performance of robotic and prosthetic hands.

Keywords: Human hands, dexterous manipulation, haptic interfaces, robot hands

Index Terms: Human performance, human factors and ergonomics, biomechanics

1 INTRODUCTION

Understanding the human hand's kinematic capability during dexterous, within-hand manipulation is beneficial in many domains. In robotics and prosthetics, understanding kinematics can help benchmark existing hands [1], [2] or drive the design of future ones [3]. In the medical domain, knowing the kinematics of a healthy hand can help to better target rehabilitation [4] or surgery of an impaired hand [5]. In the area of haptic devices, understanding the kinematics of natural human finger motions can help to design devices for hand motions which are feasible and comfortable for the end user [6].

The current work seeks to experimentally determine the *precision manipulation workspace* of the human hand. We define this workspace as the range of motions through which a person can feasibly move an object held the fingertips, without removing or replacing the contact, or allowing the object to slide along the fingertips [7]. Fig. 1 shows the object used to evaluate precision manipulation workspace in this study. The precision manipulation workspace can be easily related to tasks such as writing or using a haptic input device (e.g. [8], [9]) which can be held in the fingers. It could also be used to analyze related motions, such as pinch gestures for a touch screen.

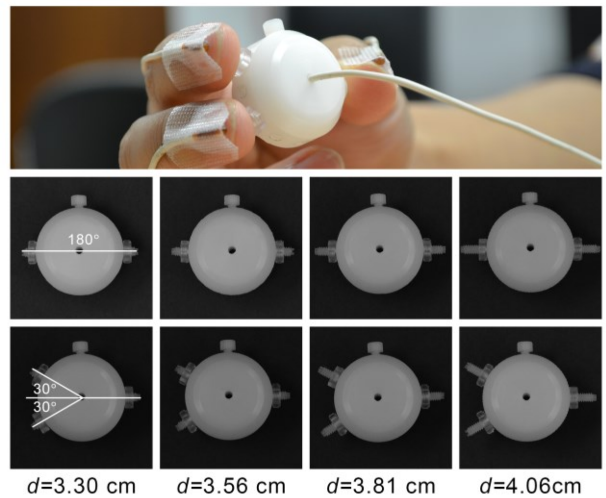

Figure 1: Pointed object used for manipulation in this study. All sizes used for the two and three-fingered objects are shown. Object size was scaled according to participant hand length.

We also examine the tradeoffs in manipulation workspace between using two and three fingers. While using three or more fingers may give additional stability, we hypothesized that the precision manipulation workspace where only the thumb and index finger are used would be larger than when the middle finger is also involved. The main reason for this expected reduction is that an additional finger adds kinematic constraints that must also be satisfied throughout the workspace.

The remainder of this paper is structured as follows. The next section provides an overview of related work, particularly hand workspace estimation. Section 3 describes the experimental methodology used. Section 4 provides representative 3D workspaces and the overall volume trends for all participants. Section 5 analyzes the workspaces and trends and discusses some applications. Finally, section 6 concludes the paper with a discussion of limitations of the study and potential future work.

2 BACKGROUND

Our current work differs from existing work by studying the within-hand kinematic workspace of human precision manipulation of a real non-zero size object. Some existing work which has looked at related tasks will be discussed.

Kuo et al. [10] examined *functional workspace* of 20 participants by calculating the area of intersection of the free thumb and finger trajectories, to estimate the ability of the hand to move a small object within a precision pinch grasp. The work illustrates the resulting 3D workspaces and analyzes relationships between finger length and the workspace for each thumb-finger

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combination. A follow-on work does some additional fitting of the resulting shapes [11]. However, the current work differs by analyzing manipulation workspace of a real non-zero size object directly, and considers workspace as a 3D volume rather than the simplified 3D surface used in [10].

Youm et al. [12] modeled a workspace using a technique similar to the Kuo et al. [10] workspace intersection method. However, this work models only a planar workspace, assuming that manipulation in a three-fingered grasp is always along the medial plane of the hand. The present work does not make this simplifying assumption and considers experimental data for the full 3D workspace.

The manipulability of the thumb and index finger pinch in three postures is analyzed in [13]. The results indicate, for example, that the index finger posture plays a greater role in determining manipulability than the thumb posture. This work differs because it considers only three poses with a small stick object and focuses on manipulability, rather than the current work's larger object and continuous kinematic view.

Some work in the robotic domain has looked at precision manipulation workspace. For example, Borras et al. [14] looks at the workspace of a three-fingered symmetric robotic hand using a framework inspired from the parallel platform literature. Odhner et al. [15] analyzed planar workspace of a symmetric, underactuated two-finger hand. Ma et al. [16] applies a linkage-based analysis to the workspace of a similar hand. Finally, Cui and Dai [17] analyzes how a flexible palm influences the workspace and manipulability of the three fingered metamorphic hand. The present work differs from previous robotic efforts in that it looks at the specific case of the human hand, taking an experimental approach to assessing the workspace.

Some works have looked at related tasks, but from a force perspective rather than a kinematic perspective. Rácz et al. [18] looked at the force coordination patterns of the thumb, index, and middle fingers while performing simple tasks with a three-load cell object. Their results indicate a strong synchrony of normal force modulation by each finger during the tasks tested. However, this work did not involve significant displacement of the overall object. Many motor control related works do study finger forces in detail - see [19] for a review. However, these works generally look at forces and overall hand and arm movements, rather than the kinematics and within-hand behavior that are the focus of the present work.

Finally, Gilster et al. [20] looked at the finger contact points used during grasping and lifting of a cylinder and other objects. This study indicates comfortable grasp point positions for a three-fingered cylinder grasp are to have the index and middle finger positions at approximately $\pm 20-30°$ relative to a position opposite the thumb. This helped us decide on using angles of $\pm 30°$ (see Fig. 1) for comfortable grasp points on the pointed object used in this study.

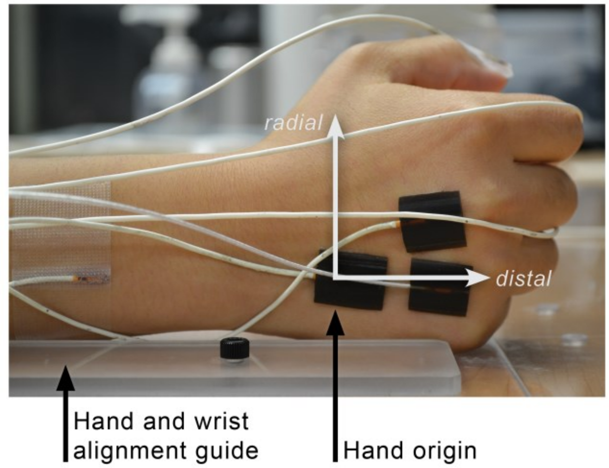

Figure 2: Experimental posture and hand reference frame.

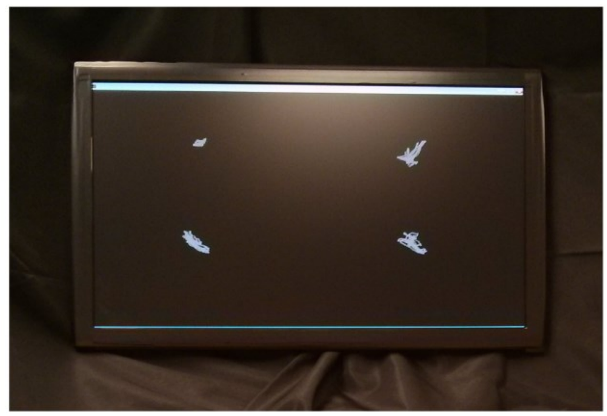
Figure 3: Visual feedback of four views of the workspace traced out is provided on a 27" LCD display. Curtains were used around the monitor to reduce visual distractions.

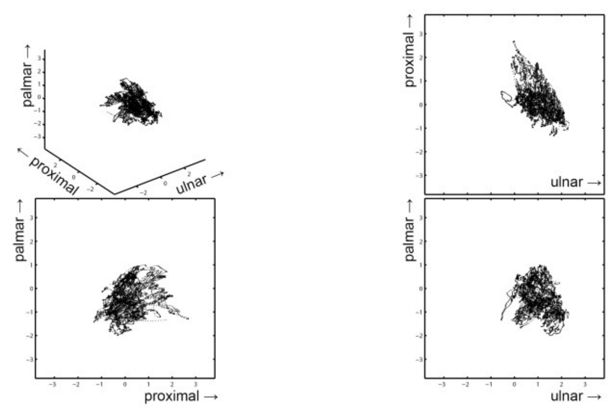

Figure 4: Diagram of the four visual feedback views used, corresponding to the same four corners of the participant display in Figure 3. A different example trial from the one in Fig. 3 is shown. All units are centimeters.

3 METHODS

Our general experimental protocol involves unimpaired human subjects manipulating a pointed object (Fig. 1) held between the thumb and forefinger or thumb, forefinger, and middle finger, while the relative position of the object with respect to a hand base coordinate frame is measured. Magnetic tracker sensors (Fig. 2) and visual feedback (Fig. 3 and 4) are used.

3.1 Participants

19 participants completed the experiment. They are aged 18-31 (median 25), with 6 male and 13 female participants. Participants were recruited from the local New Haven community; most are graduate students. Hand length ranged from 15.5 to 19.8 cm, with a median hand length of 17.5 cm. The measurement setup required that all subjects are right handed and have normal hand function. The study was approved by the local IRB.

3.2 Equipment

A trakSTAR magnetic tracking system (Ascension Technologies, Burlington, VT) with a medium range transmitter (MRT) and eight MODEL 180 2 mm diameter sensors was used. Each system provides 6 DOF data at the configured, recommended sampling rate of 80 Hz. The positional accuracy of the system is 1.4 mm RMS and the angular accuracy is 0.5° RMS. The three bare trakSTAR sensors to be placed on the back of the hand were inserted into small rubber sleeves (see Fig. 2) to reduce unintended rotation around the long axis of the sensor during the experiment. The object sensor was fixed in the center of the object using a nylon set screw.

A single Point Grey Flea3 USB3 camera with a Fujifilm 2.8-8 mm F1.2 lens hanging from the ceiling about 1.5 m away provides 20 fps 320x240 reference video. The video footage serves as an additional reference in case any trials need to be examined.

The pointed, cylindrical object shown in Fig. 1, referred to from here on as the "pointed object," was machined to allow three adjustable 4-40 nylon setscrew finger contact points at 30 degree angle increments. The final object has a mass of 11 g. These were set to provide 3.30, 3.56, 3.81, or 4.06 cm effective diameter, depending on participant hand length. One of these diameters was selected to be closest to a target diameter specified by the equation $d = 0.2l_h$, where d is object diameter and l_h is hand length (tip of middle finger to palmar wrist crease), both in cm. This scaling factor was picked based on anthropometric data [21] to allow object scaling from a 1% female hand to a 99% male hand, as well as informal tests that showed this to be a comfortable object size that ought to give a large workspace.

Visual feedback was provided on a 27" LCD monitor 1 m in front of the experimental table to help participants thoroughly explore their position workspace; an example screen can be seen in Fig. 3, with a diagram of the views used in Fig. 4. Three views were aligned with two anatomical axes of the hand (distal-proximal, radial-ulnar, dorsal-palmar), while the fourth view was a perspective view. During each trial, participants were instructed to visually trace out as large a workspace volume as possible, and to fill in this volume as best they can. A goal-based variant of this visual-feedback exploration approach was considered, but ultimately decided against due to the added risk of biasing the results based on the goal characteristics, rather than capturing a more natural range of movement.

3.3 Procedure

Some preparation was performed before the experiment. First, the participants removed any 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 in detail. Participants were instructed to minimize any sliding of the pointed object at the pointed set screw contact points, and to make sure that the initial contact points were within the area of the distal half of each finger pad used. Participants were also instructed to avoid removing any fingers from the object during a trial. In this manner, the participant is 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. 2. 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 [21]. The hand position for the trials can be seen in Fig. 2. 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 base frame movements due to skin motion.

For this work, two blocks of trials involving a pointed object (Fig. 1) manipulated with two and three fingers will be considered. The full study did include additional trials with a spherical 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. 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. 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.

3.4 Workspace Volume Calculation

A voxel binning method was used to calculate the workspace volume, similar to that used in [1]. Specifically, workspace points from each trial were binned into a three dimensional grid of voxels. The grid spacing, or size of each bin, was set using a 95% confidence interval for the deviation of the hand reference frame sensor points, which is 2.15 mm. This number sets a reasonable range within which workspace points cannot be effectively discriminated. The effect of bin size on resulting workspace volume was evaluated, and it was determined that volume increases roughly linearly with increasing voxel size. This linear scaling makes the ratio of the workspaces more meaningful than the absolute values. It was also confirmed qualitatively that 2.15mm is a large enough voxel edge width to prevent frequent holes in the workspace volumes due to sparse data points. The voxel grid begins exactly at the minimum x, y, and z values for a trial, and ends at the maximum values. The final volume is calculated as the sum of the individual voxel volumes that contain at least one data point.

4 Results

Several statistical tests were performed initially to check for any complicating effects in the data set. It was found that hand length significantly affects the resulting workspace ($p = 0.001$). The effect of sex on volume is almost significant ($p = 0.07$), but if the effect of hand length on volume is taken into account, this effect is no longer significant ($p = 0.49$). It was initially hypothesized that workspace volume might increase with participant experience over the course of the entire study, but this effect is not significant ($p = 0.6$). On average, the workspace volume increased a modest 24% from the first to third trial of each block, but this effect is not statistically significant ($p = 0.3$). After accounting for hand length effects, any effects of the

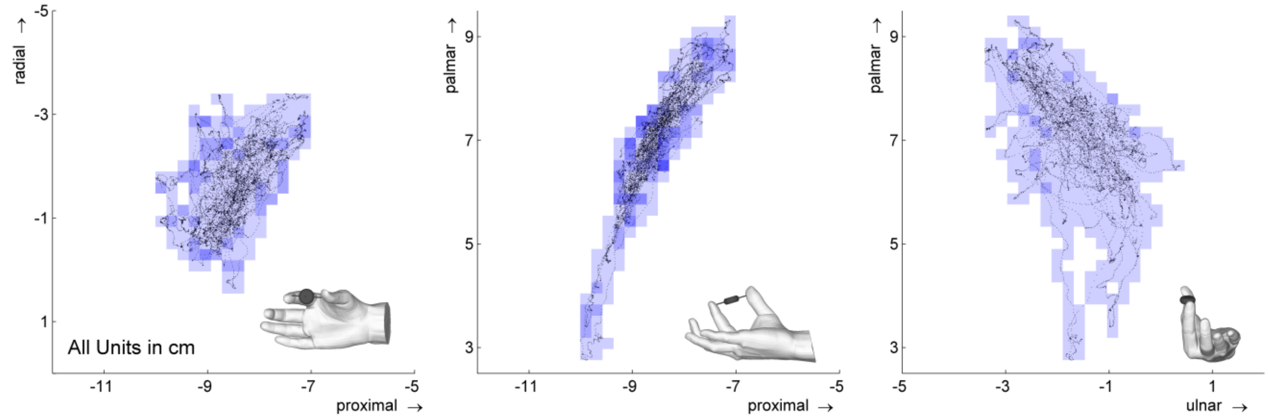

Figure 5: Two finger workspace from subject 16. Hand length is 17.5 cm, volume is 6.79 cm³. Workspaces from other subjects look similar. The black dots represent the locations of the center of the object and the blue shaded area shows the volume. A darker shading indicates that more voxels are stacked in the direction perpendicular to the view. The hand rendering indicates the orientation of the hand in that view, 3D models are taken from [23] and do not necessarily represent a hand configuration that was used during the workspace trial.

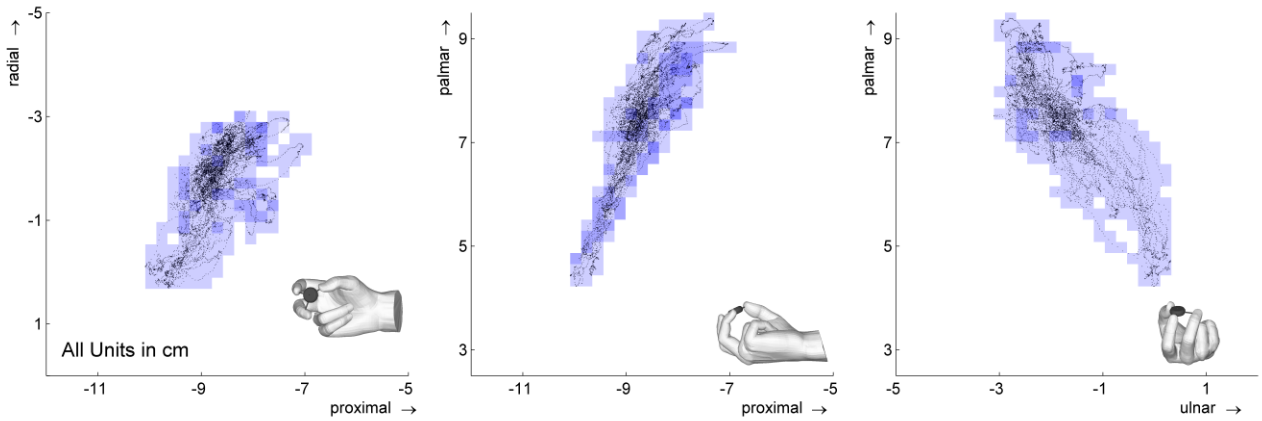

Figure 6: Three finger workspace from subject 16. Volume is 6.18 cm³.

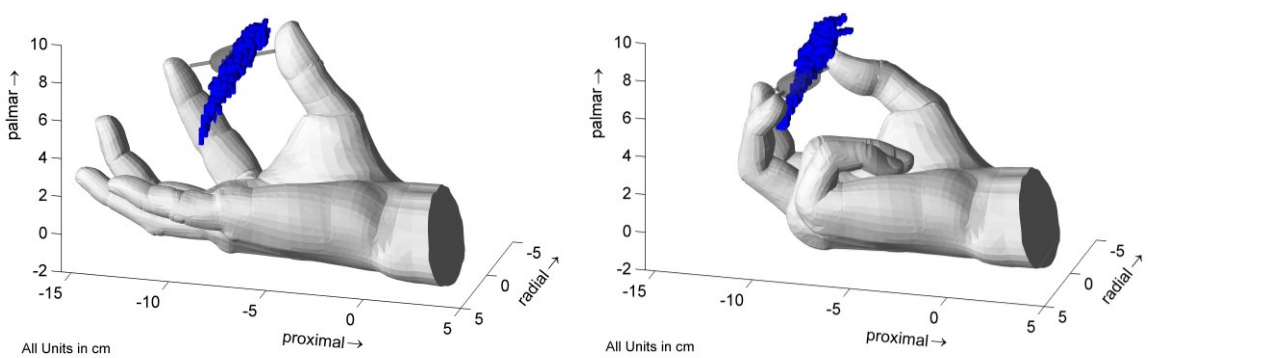

Figure 7: Subject 16 two (left) and three (right) finger workspaces, 3D view. Note that the hand model gives a general indication of workspace position and orientation within the hand but is not an exact model of the participant's hand.

diameter the object is set to are not significant ($p = 0.8$). Following this initial analysis, sex and any trial order effects were not considered in the following.

First, a representative workspace of subject 16 is shown in several views. The two and three-fingered workspaces are shown in Fig. 5, 6, and 7. All axes have units of centimeters with no normalization applied. The subject shown has a hand length of 17.5 cm, which was the median for this study. The 3D hand model is provided only to indicate the alignment of the plots with the anatomical hand axes and should not be considered an accurate model of the participant's hand. Overall, the 2-finger workspace shown is similar in shape to the 3-finger workspace, but the 3-finger workspace does not extend as far in certain directions.

The workspace volumes for every participant are shown in Fig. 8. A few outliers exist, namely subject ID 4 and 15. Based on the notes and observations during the experiment, it does not appear that constraints were violated in these cases, but rather that these individuals were able to move their hand with greater flexibility

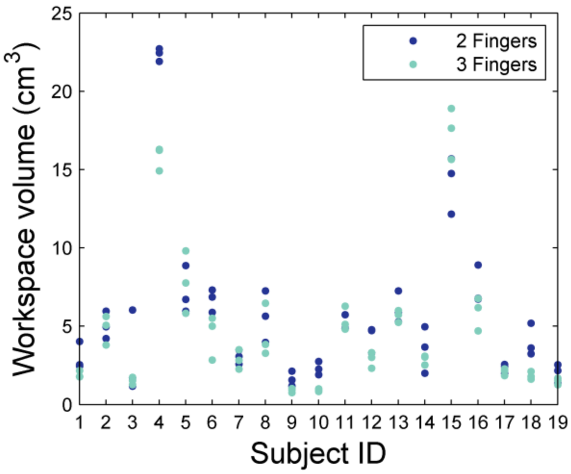

Figure 8: Workspace volume results for each subject. Each subject performed the 2 and 3 finger condition three times.

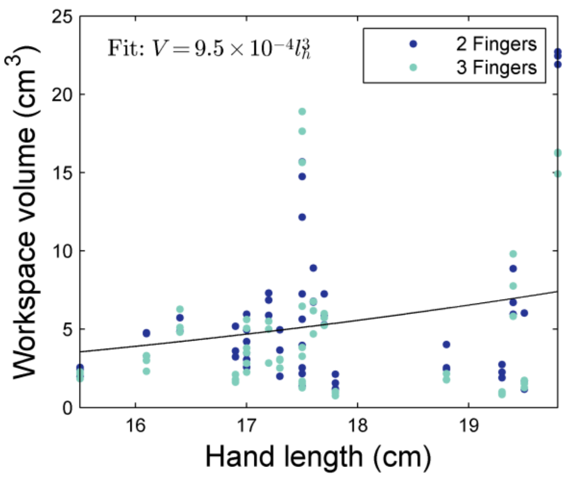

Figure 9: Workspace volumes as a function of hand length. A line was fitted to all data points and the equation is shown in the figure.

than most participants. Participant 4 does also have the largest hand recorded (length 19.8 cm), but Participant 16 has an exactly median length hand. The average workspace volume is 5.7 cm^3 for two fingers and 4.8 cm^3 for three fingers.

The relationship between workspace volume and hand length is shown in Fig. 9. It is hypothesized that volume should scale as the cube of hand length. This hypothesis should hold if the human hand scales in a manner which preserves relative link lengths and maintains constant joint limits, in which case the conversion between workspace volumes could be thought of as a simple unit conversion between link lengths (given that object size has been scaled deliberately with hand length in this study).With this hypothesized cubic model, the fitted equation obtained to calculate expected volume for a given hand length is $V = 0.000954 l_h^3$, where V is the volume in cubic centimeters and l_h is hand length in cm. The increase in volume with hand length is statistically significant, with $p = 0.001$. While the increase in volume with hand length is significant, it should be noted that the fit is affected by the outliers, and that this statistical test does not confirm whether the simple cubic model proposed is the best model.

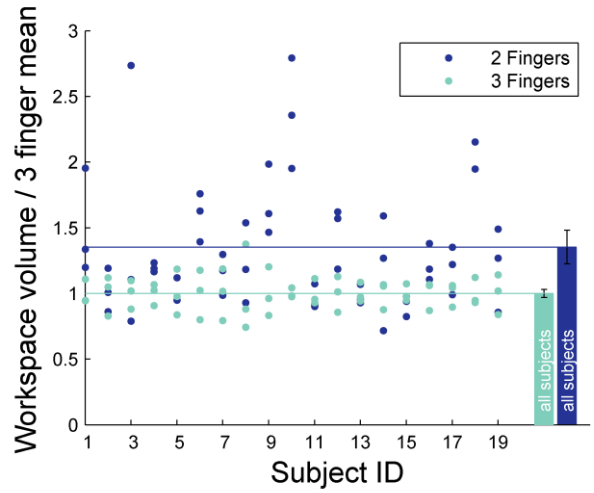

Figure 10: Workspaces volumes normalized per subject by the volume of the 3 finger workspace. On average the two finger workspace is 40 % larger than the three finger workspace. The error bars on the right correspond to a 95 % confidence interval of the mean value.

The differences between two and three-finger workspaces are shown in Fig. 10. Since there is a large amount of between-subject variability, but the trends within each subject seem more consistent, we have normalized each subject's volume based on the mean volume of the three-fingered trials for that subject. As hypothesized, the two-fingered workspaces are significantly larger overall than the three-fingered workspaces, with a paired t-test giving $p < 0.001$. On average, the two fingered workspace is 38% larger than the three fingered workspace. While this effect does hold overall, there is still a fair amount of variability between trials, and for certain subjects the effect was small or even reversed.

5 Discussion

The results presented above show typical 3D precision manipulation workspaces for a sample subject, quantified performance differences between the 19 subjects examined, the general effect of using three fingers rather than two during manipulation, and the effects of hand length on resulting workspace. These effects will now be discussed in more detail.

As one of the clearest take-aways from this work, the experimental results confirm our hypothesis that the two-fingered manipulation workspace is substantially larger than the three-fingered workspace, due to the fact that there are fewer kinematic constraints on the object in the two-fingered case. On average, the two-fingered workspace is 1.4 times the size of the three-fingered workspace for a particular subject. However, while the effect is highly significant overall in the participant population ($p < 0.001$), it does not hold for every trial or every subject.

There are some possible reasons why the volume decrease from adding a finger may not be observed in every subject, or why it is not larger in magnitude. One possible reason is that since the kinematics of the index and middle finger are fairly similar and in similar orientations, the constraints they impose may be at least partially redundant. Thus, by applying redundant kinematic constraints, the effective mobility of the system is reduced less than it would be otherwise. For example, if the manipulation of the thumb, index, and little finger were considered instead, the resulting workspace would likely be very small due to the much different kinematics and workspace of the index and little fingers. Another possibility is that since people often prefer to use more than two fingers (see e.g. [20]), they may be more accustomed to the theoretically more limited range of manipulations possible with additional fingers. It is possible that pushing with a third finger could allow subjects to use passive finger compliance to reach additional positions that are outside the two finger workspace. Finally, the added stability of an additional finger contact may make subjects more willing to explore the limits of their workspace in the three-finger case.

One interesting result of the experiment is the magnitude of the inter-subject variability in the workspace explored. For example, there were two subjects with a much higher workspace despite not appearing to violate any experimental constraints. Certain subjects who seemed particularly motivated and focused did not necessarily end up with these large workspaces. Even when the participants are instructed to try all valid hand movements that they can, it appears that subjects in general are comfortable with only a smaller range of movements. The results may suggest that some participants have a greater amount of what could be called *motor creativity* for their within-hand motions. This has important implications for interface design, as end users may only be comfortable with a much smaller range of movements than they are physically capable of. Physical flexibility of the hand could also contribute to the variability in the resulting workspaces.

The results suggest that the 3D workspace volume is longer along certain axes than others. For example, the longest axis for many participants appears to be the long, thin arc in the middle proximal-palmar plot of Fig. 5 and 6. Interfaces can be designed to take advantage of these axes where the motion range is larger, and the boundaries of the workspace indicate where wrist and arm movements will start to become necessary.

There are several possible areas of application for this work. The task examined is similar to tasks such as writing, soldering, or other precision positioning tasks. Understanding the manipulation capabilities of the fingertips can help inform the design of physical devices and software systems that interact with the hand. For example, the data presented could set limits for motion of a haptic device end effector, within which the user will not be required to move their arm. Avoiding arm movement could provide greater stability for a high precision task or simply reduce user exertion. These general motion ranges could also inform design of comfortable touch-screen, pen, or even free air hand gestures. The experimental protocol could be easily adapted to give more accurate results for these specific applications. In the domain of robotics, we anticipate the results can be used to benchmark the performance of robotic and prosthetic hands, as well as to help inspire the design of hands with similar precision manipulation capability. In the medical domain, the results could be used to help analyze trade-offs between within-hand and whole-arm movement in surgical technique [22], such as with a scalpel or robotic surgery tool [8].

6 Limitations and Future Work

There are a number of extensions to the results shown in this paper that we plan to address in successive studies. The scope of our current work is limited to analyzing the details of the position workspace for a single object. This workspace could be affected by object geometry, task force requirements, and task kinematic constraints. Some of the simplest extensions involve investigating additional object sizes and shapes, for which we expect the size of the workspace to change, but the overall shape and orientation to remain similar. In addition, successive work will examine the object orientation workspace, which will be important for many tasks and applications. Longer-term work could examine more complex dexterous manipulation tasks involving substantial finger-gaiting, sliding at contacts, or removal/addition of fingers during the task. Despite the large number of future directions, we anticipate that the results of this study will provide useful information in various domains, such as robotics, prosthetics, and haptic interface design.

Acknowledgments

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