Rotational Ranges of Human Precision Manipulation When Grasping Objects With Two to Five Digits

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***Abstract*— The ability to move and manipulate objects within the hand is important for the overall performance of the human hand. Such movements are key for many tasks, including writing, using precision tools, turning knobs, and operating various haptic interfaces. In this work we analyze the ability of 17 unimpaired subjects to rotate objects 50 and 80 mm in diameter using 2 to 5 digits, while maintaining the initial finger-object contact locations. Subjects were asked to rotate the object with a particular number of fingers around one of three orthogonal hand axes for 30 seconds and explore their rotational range. The average rotational range achieved over all conditions was 47 degrees, with the largest rotation of 82 degrees for the 3 digit case around a distal-proximal axis. The rotations around the palmar-dorsal and the ulnar-radial axes showed similar trends, where the smaller object resulted in 1.3 and 1.2 times larger rotation workspaces than the larger object ($p < 0.001$), respectively. The rotation around the distal-proximal axis has a different trend, where the difference in rotation amplitude between different number of finger conditions is over 50% ($p < 0.003$), but the difference in object size conditions is only 10%. The results highlight that the orientation of the rotation axis has significant influence on the rotation capabilities of the human hand. In designing handheld tools and haptic devices one should carefully consider around which axes a rotation is required.**

I. Introduction

Human dexterity is complex and is still not fully understood. We are able to manipulate and move objects within our hand with great precision and security. Compared to current artificial systems, both in prosthetics and robotics, there is still a large gap, as those hands have very limited in-hand manipulation capabilities [1]. In this work, we focus on in-hand motion where the object is held with a specific number of digits and the contact with the object is not changed. Specifically, we look at the rotational ranges the human hand can achieve under this condition around the three major axes of the hand (distal-proximal, palmar-dorsal, and ulnar-radial). Such in-hand manipulation capabilities greatly add to the functionality of the human upper extremity, as it allows manipulation of the object without the need to invoke arm motions. In particular for rotation, the object can be rotated by an axis that passes through the object, which cannot generally be achieved otherwise. This particular movement type is helpful in constrained spaces, reduces the energy requirements, adds to the total rotational range and can increase the precision of object rotation.

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Analyzing human object rotation capabilities can help provide benchmarks and inspiration for prosthetic and robotic hand design [1]–[4]. For hand rehabilitation it enables the pinpointing of critical movements that are important for normal hand function [5]. Haptic interfaces, such as those used in surgical robots [6], will also profit as the human capabilities are better understood. It allows for the alignment of the human hand with the workspace of the device, improving overall performance [7]. This work can also provide insight into the number of fingers that should be used for such a device.

Prior research has focused on examining the positional workspace of human hands, in particular of the thumb and index finger. Approaches to determining the thumb-index workspaces included intersecting the free motion workspaces of thumb and index finger [8] and fit shapes into the workspace [9]. Previous work by the authors experimentally measured the two and three finger translational workspace using a similar methodology [10]. The major difference is that this paper focuses on rotational workspaces.

It has been shown that the number of fingers changes with the size and mass of the object [11], [12]. In that respect, adding more fingers increases the hands' ability to resist forces and grasp larger objects. Also, the individual contact forces are regulated with the goal to minimize the overall force, while maintaining stability [13]. In a five finger grasp, the forces of the individual fingers are different, contributing to shear and normal forces in different amounts. Our research will add to this existing knowledge of how the number of fingers affects capabilities of a hand, in particular for rotational capabilities.

In robotics, there has been some effort towards optimizing and analyzing in hand manipulation, such as using methods from the parallel platform community [14], applying a linkage-based analysis [15] and using a boundary based method [16]. Those methods provide insights into the mechanisms that increase the workspace of a particular hand. Our approach differs as we experimentally examine the human rotation workspace, providing benchmark data for the robotics community.

II. Methods

We aim to estimate the rotation capabilities of unimpaired subjects when rotating objects of different sizes with a varying number of fingers. Subjects were instructed to rotate the sensorized object back and forth, exploring their rotational range around a particular axis. The object's current angle was projected onto a line and displayed on a screen as feedback for the subjects (Fig. 2). The study was approved by the local IRB.

A. *Participants*

Overall, 17 healthy unimpaired, right handed subjects participated in our experiment. They were recruited with flyers

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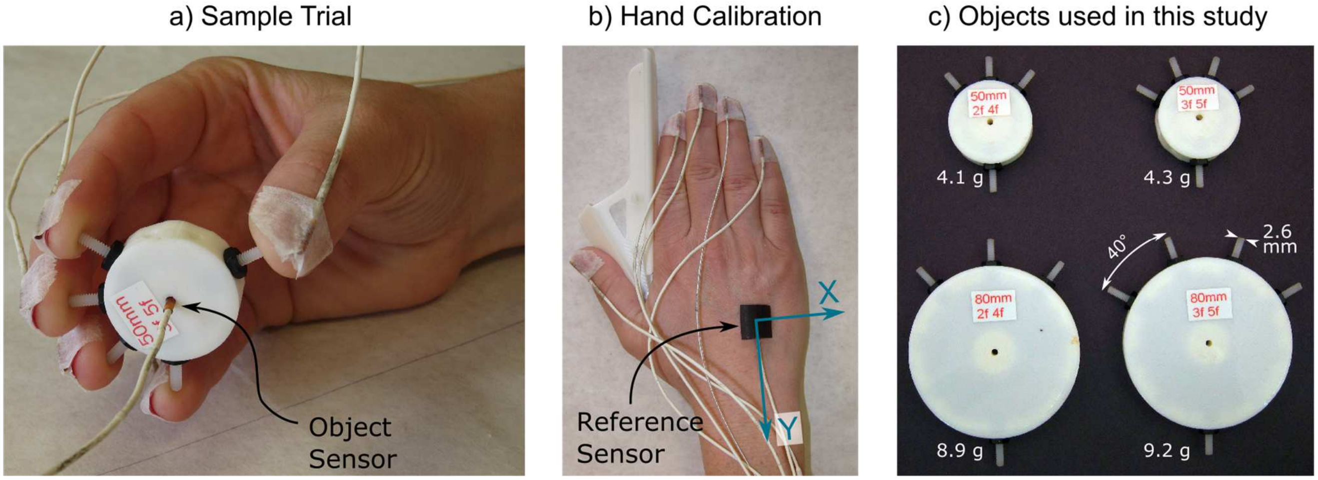

Figure 1. a) Sample trial of the 5 digit case with the 50 mm object. The object sensor is placed in the center of the object and the fingertips are used to grasp the five pointed contact locations of the object. b) The hand in the calibration setup. This step is important as it defines the rotational axes. c) The four objects used in this study and their properties. The small objects have a diameter of 50mm (including the screw lengths), whereas the large object is 80 mm.

and by personal communication. Most participants were students or other people affiliated with the university. Ten subjects were male and seven female. The mean hand length is 18.1 cm (males: 18.47 cm, females: 17.5 cm) and the mean age is 26.9 years (range: 21 – 41 years).

B. Equipment

To record the motions, a trakSTAR magnetic tracking system (Ascension Technologies, Burlington, VT) with a medium range transmitter and eight Model 180 2 mm diameter sensors was used. Each sensor provides 6D information of both position and rotation with respect to the base station. The sampling rate was kept at the standard rate of 80 Hz. The positional accuracy of the system is 1.4 mm RMS and the angular accuracy is 0.5° RMS.

Figure 1 shows the object and the configuration of the finger contact pins. Two object sizes and four finger conditions were used for this experiment. The small object had a diameter of 50 mm and the large object had a diameter of 80 mm. As contact locations of the fingers a 4-4- nylon setscrew was used, which provided "pointed" contact locations with a diameter of 2.6 mm. Using a small contact diameter, the finger-object contact is similar to a point contact, preventing rolling. Slippage, however, cannot be completely prevented and can still occur. The finger positions on the object were chosen so that the thumb perfectly opposes the fingers in contact with the object. The finger spacing was selected according to a study, which found consistent angular patterns for finger placement [17]. We use an offset of 40 degrees between fingers, which is inspired by this study. Note that we only used 4 objects, as each object allows direct finger-thumb opposition for two different finger conditions. For the lower number of digits, the two outermost pins would not be touched.

To provide visual feedback to the participants, a 27" screen was placed in front of the subjects, about 1.5m away from the subjects. As seen in Fig. 2, the top part of the screen showed an image indicating the particular rotation axis for that trial. The bottom part showed a red dot representing the current rotation, providing instant feedback. A white vertical line showed the zero position. We deliberately chose not to show information on the previously explored rotational range (e.g. showing the highest achieved rotation so far in this trial), as this might have introduced a bias into our analysis. Not providing them any clues on their previous rotations forced the participants to focus on exploring their actual kinematic limits.

C. Procedure

First, subjects were introduced to our experiment and the rotations we were interested in. We showed sample videos of rotations around the three axes and explained the motions for the three different rotation conditions (see Fig. 2). Then the hand proportions were measured, including hand length and hand width [18]. Afterwards the sensors were attached to the hand, as shown in Fig. 1. Double sided tape (Vapon Topstick® Men's Grooming Tape) was put onto the nail and the sensor was placed on it. Then 3M Transpore™ tape was placed on top of the sensor to further secure it. The reference sensor (Fig. 1b), on the back of the hand was inserted into 1.5x1.5x0.3cm rubber sleeve that was secured to the back of the hand with Vapon Topstick® Men's Grooming Tape. Additionally, 3M Transpore™ was put on top of the sleeve and about 1cm of cable. The cables coming from the hand were fixated to the arm with loop straps and the cable was draped over the participant's shoulder, providing strain relief. The cable length was adjusted to prevent pulling on the sensors when closing the hand and to preclude the excess cable from interfering.

The object sensor was placed into a correctly spaced hole in the center of the object and was secured with a set screw. The object had to be changed depending on the trial, thus we ensured that the sensor was removable.

24 different conditions were tested. There were four different digit conditions (2-5 digits in contact with the object), two object sizes (50 mm, 80 mm) and rotations around the three major axes (X, Y, Z). As each condition was repeated twice, there were 48 trials performed in the course of the experiment. This resulted in about 1 hour of actual experimentation. The experiment was structured in two parts, where each part contains all 24 conditions in random order. To simplify the experiment, the three rotation conditions for a particular finger count and object size combination were done in one block, reducing the number of object changes. Each trial took 30 seconds with a 10 second break in between.

Before each block of X, Y, and Z rotation, there was a training period, where the subjects could familiarize

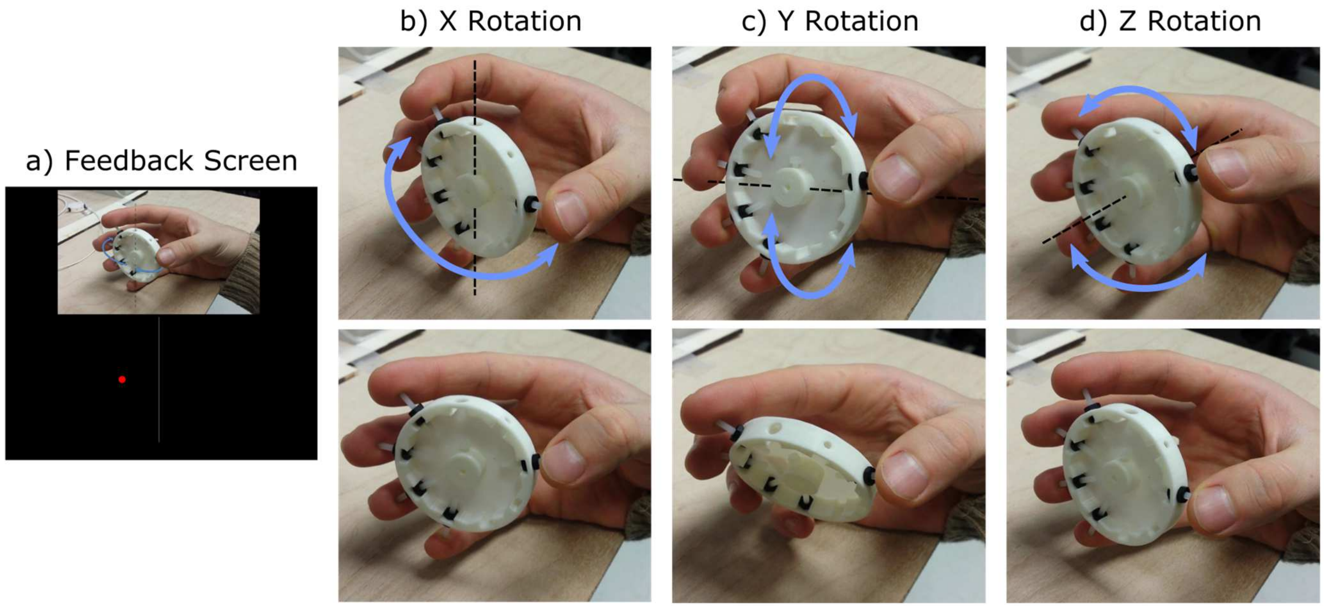

Figure 2. a) Feedback screen; Top images indicate the rotation the subject is supposed to perform during the experiment. The red dot indicates the current rotation around the given axis and the white line indicates zero. The subject is asked to move the point left and right by rotating the object. b-d) Images indicating the three rotation directions that were used in this study. For each rotation two images (top and bottom row) are given, indicating the motion.

themselves with the particular condition and practice rotating the object. On screen feedback was provided for all three rotations simultaneously. The subjects indicated when they were ready to start the experiment. Then the hand and object were calibrated for the three subsequent trials. During the trial subjects were instructed to keep the forearm on the table, aligned with a rail of 5mm height. The ulnar side of the hand had to touch the table as well to reduce skin motion under the reference sensor.

D. *Rotation Angle Calculation*

The output from the trakSTAR is a 3x3 rotation matrix r that encodes the orientation of the object with respect to the hand coordinate frame. Based on this information, the orientation of the object with the three global coordinate axes is sought. We use an X-Y-Z fixed angle representation, a particular three-angle representation [19, p. 12] of X (ψ), Y(θ), Z(ϕ):

$$\theta = Atan2(-r_{31}, \sqrt{r_{11}^2 + r_{21}^2})$$

$$\psi = Atan2(\frac{r_{21}}{cos\theta}, \frac{r_{11}}{cos\theta})$$

$$\phi = Atan2(\frac{r_{32}}{cos\theta}, \frac{r_{33}}{cos\theta})$$

For the X and Z rotation, the rotation angle can be between ±180 degrees and for Y the rotation ± 90 degrees to give the correct rotation. Angles beyond that either jump by 360 degrees (X, Z) or jump to a different solution (Y). As shown in Fig. 3, tests with simulated data confirmed that this representation allows the extraction of the three global rotation angles. A rotation matrix is created by multiplying together individual rotation matrices along X, Y, and Z. The direction along which the rotation is measured (primary rotation) is set to a certain input rotation. The two other rotations (secondary rotations) are given random rotations of the given noise level. Then, based on this rotation matrix, the X, Y, and Z rotations are extracted. For each angle (from -180 to 180 degrees in 6 degrees steps) this is repeated 1000 times and the 90th percentile is used as error representation. Even when there is a noise of up to ±40 degrees, the estimation still works reliably, however the ranges that return meaningful data are reduced. The error magnitude in the primary rotation is always smaller than the amount of noise in the secondary rotations.

In the two digit trials, the object is only held at two points, therefore it is not fully constrained in space. The rotation around the axis connecting the two contact locations cannot be fully controlled; the object could potentially spin around this axis. During the experiments, we paid special attention to the cable of the object sensor, making sure it always pointed in the same direction. This way the cable from the object sensor was used to prevent excessive rotations. However, this only prevented the object from rotating by more than about 90 degrees.

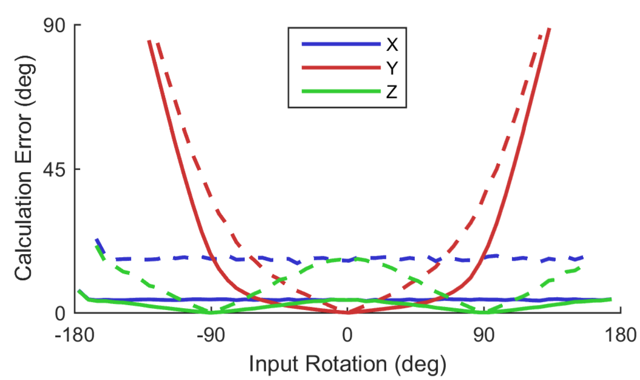

Figure 3. Error Estimation of the rotation angle calculation. For each coordinate, the real rotation matrix is multiplied with rotations around the two other axis with a random error (solid line 20 deg, dashed line 40 deg). The lines give the 90 percentile difference between the actual rotation and the calculated rotation. The rotation estimation is influenced by the secondary rotations, however their influence is smaller than their magnitude. X and Z rotations are stable from almost -180 to 180 degrees, whereas Y is stable in an interval of less than [-90,90], depending on the amount of noise.

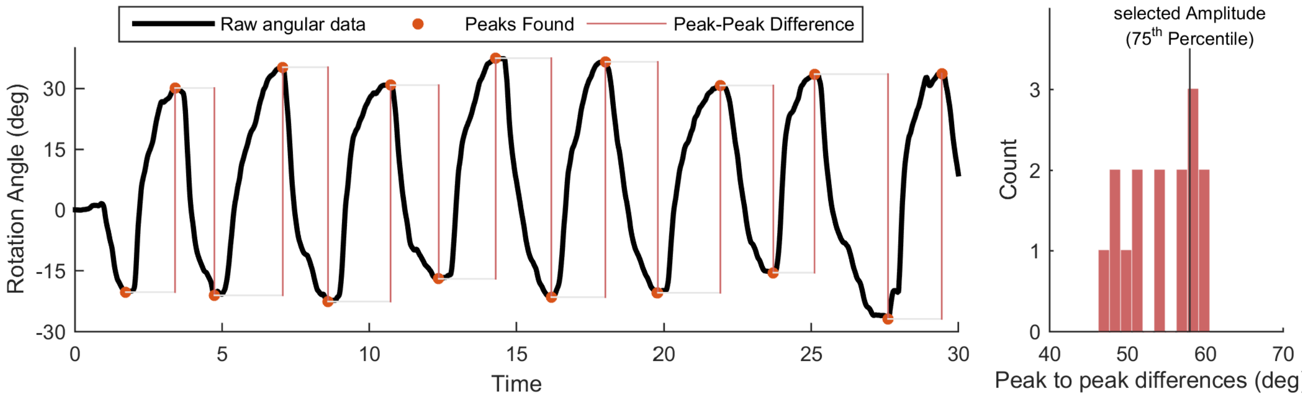

Figure 4. The left plot shows the raw data around the primary rotation, the peaks found and indicates the peak to peak differences that were calculated. The right plot shows a histogram of the peak-to-peak differences. The 75th percentile is selected as the representative rotational amplitude. For visualization purposes a trial with few peaks (16) was chosen. The fastest trials have up to 90 peaks.

E. Rotational Workspace Calculation

For each 30 s trial, as shown in Fig. 4, the rotational workspace needs to be computed. Therefore, the following steps are performed:

1) Detect the minima and maxima in the trial. We use the Matlab function "findpeaks" with the prominence parameter set to 1/8th of the total observed angular range. Using this function the extremes in the dataset are detected very reliably. The number of peaks (both maxima and minima) ranged from 6 peaks up to 99 peaks for the 30 s trial.

2) Check that the minima and maxima are alternating in the dataset. If not remove the second peak. Only 5 peaks had to be removed for the whole experiment.

3) Calculate the difference between min/max of adjacent peaks. The vertical red lines in the left plot in Fig. 4 indicate those differences. Using the peak differences avoids problems with drift, which occurs in some trials.

4) The 75th percentile of the differences is taken as the rotational amplitude. We feel that looking at only the mean of the peak to peak differences could underestimate the maximal rotational range, whereas taking the maximal observed peak to peak difference is prone to outliers. We chose the 75th percentile as it is in between the average rotational range and the maximal observed range.

III. RESULTS

Overall, 17 subjects participated in the experiment and all subjects were able to complete all the trials. For the first two subjects, the two finger trials were not performed. As the rest of the protocol was identical, we include these subjects in our data. This results in 792 individual trials, each 30 s long. Subjects gained experience over the course of the trial, the second trial of the same condition was on average 16.9±4% larger, where 61% of the trials showed an increase in rotation amplitude. There is a positive relationship between the hand length and the rotation amplitude ($p < 0.001$, F-test on linear regression model). More specifically, in the two digit case, the hand length does not significantly correlate to the workspace ($p = 0.7/0.8/0.07$ for X/Y/Z, F-test on linear regression model). For X and Z rotations, there is a clear trend that the workspace increases with hand length for 3-5 digits, with $p < 0.004$ (F-test on linear regression model). The trend is less pronounced in Y, where the p value is around the significance threshold ($p = 0.02/0.07/0.04$ for 3/4/5 digits, F-test on linear regression model). On average males have a rotational amplitude 1.14 times the female amplitude ($p = 0.001$, two sample t-test). Even when dividing the workspaces by the individual hand length, the male workspace is 1.09 times the size of the female workspace (p = 0.02, two sample t-test).

Fig. 5 shows an overview of the rotational amplitudes for the different experimental conditions. The average rotation over all conditions is 47 degrees. The largest rotational range are achieved in the 3 digit Y rotation with a mean rotation amplitude of 82 degrees. The mean coefficient of variation (standard deviation / mean) is 40%, with a range of 20 – 76%. In all object size and number of digit combinations the Z rotation had the smallest coefficient of variation.

The rotation amplitude along X shows a low dependency on the number of fingers. The largest difference that was found to be significant was the difference for the 80mm object from 2 to 3 digits. In this case the difference was 30%, with $p = 0.02$ (all following P-values come from a paired t-test, not corrected for multiple comparisons). The median rotational range of the small object is 1.3 times larger than the large object (p < 0.001).

The Y rotation shows a different behavior to the X and Z rotation. In this case the rotation amplitude changes significantly with the number of fingers (p < 0.003). The relative differences are over 100%, between the 2 digit and 3 digit condition. The difference from 3 digits to 5 digits is 53% and the average rotation amplitudes are 22, 76, 64, 45 degrees, for 2, 3, 4, 5 digits, respectively. Regarding the object size, the 3 digit (p = 0.007) and 5 digit (p = 0.001) case are significantly different. The median ratio between small and large object is 1.1 (p = 0.03).

The Z rotations have a similar behavior to the X rotations. The number of fingers does not strongly influence the rotation amplitude, where the largest significant difference is for the 80mm object the difference between the 4 and 5 digit condition (22%, p < 0.001). Regarding the object size, all differences are significant (p = 0.03/ 2e-4/ 0.003/ 4e-8 for 2/3/4/5 digits). The median rotation amplitude for the small object is 1.2 times larger than the large object (p < 0.001).

The experimenter observed the subjects and noted when they repositioned the object (using the left hand to briefly hold the object, while the right hand re-grasped the object) or dropped the object. Fig. 6 shows the statistics for these cases. The object sizes were merged, as the difference was not found to be statistically significant (z < 1.4, two-proportion z test).

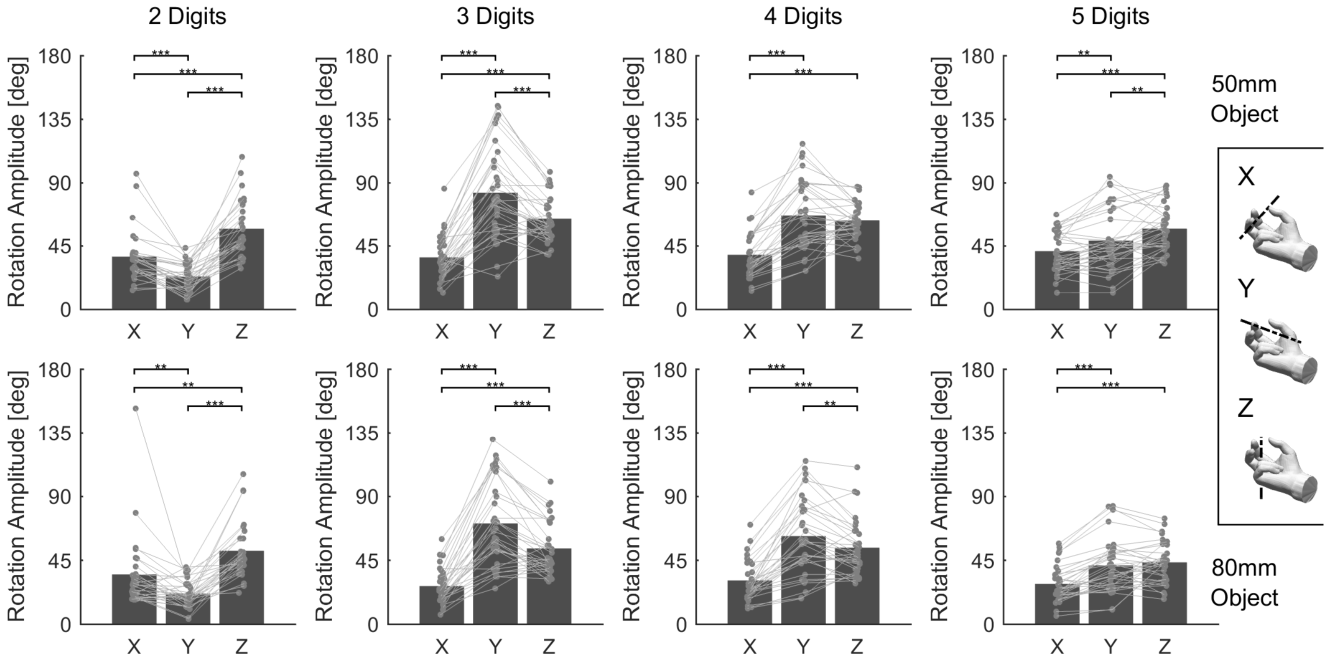

Figure 5. Overview of the rotational ranges for all 24 conditions. The lines connect the results of a particular subject for one X,Y,Z block. The significance levels for the differences between rotation axes is given in the image, the other significances are described in the text. The three hand images on the right indicate the directions of the three rotations in the experiment. The rop row corresponds to the 50 mm object, whereas the bottom row corresponds to the 80 mm object.* denotes $p<0.05$, ** denotes $p<0.01$, and *** denotes $p<0.001$.

The figure shows a clear trend that with increasing numbers of digits the percent of dropped and repositioned objects goes down. Only the Y - 2 digit case has a lower error rate, as compared to three digits. For X and Z the only non-significant difference is between 4 and 5 digits, whereas for Y the 3 finger case is significantly different from the rest.

IV. Discussion and Conclusion

In our previous work exploring the translational 3D workspace, there was considerable subject to subject variation [10]. Apart from anatomical differences, there might be also a personal factor present, where some subjects might be willing to go closer to the stability limits and/or are more creative in their workspace exploration [10]. Using a 1 dimensional exploration we hoped to reduce the influence of motor creativity. As can be seen in Fig. 5, there is still considerable variation present with differences of more than a factor of 2 for the same condition. Analyzing the object – fingertip angle might provide an additional limiting factor in this experiment.

The X and Z rotations are in many ways similar. In both conditions the number of fingers influences the workspace less than the object size. The motions of the individual fingers in these cases are similar – all move synchronized in the same direction. The constraints of adding an additional finger might be small and offset by added extra stability. This result is different from translational 3D exploration, in which case the workspace decreases with number of fingers [10]. The Y rotation requires a different movement scheme. For example in the three digit case, the index finger has to flex, whereas the middle finger has to extend in order to rotate the object. This scheme also explains why the rotation amplitude is reduced when fingers are added. Due to the larger effective radius of the object, a similar translation of the fingers results in a smaller rotation of the object. Regarding artificial hand design, the results indicate, that the selected rotation axis has a large influence on the rotation amplitude. Therefore it is important to define the axes a hand is supposed to rotate an object about and design the kinematic structure accordingly.

The two finger case is problematic, as the rotation of the object around the axis of the contact points cannot be controlled. As we felt the two fingered case is important, we chose to perform that condition nonetheless. In particular the Y-rotation may be inaccurate, since the uncontrollable axis is almost parallel to Y. This is the reason why it produced very small rotation amplitudes. Even though we did explain this problem to the subjects, to avoid introducing any bias, several subjects commented that the 2 digit, Y rotation task is difficult or impossible. This result highlights, that for haptic devices where the full 6D pose is supposed to be controlled, it is not sufficient to only use 2 fingers.

There is a clear trend that with increased number of fingers, the frequency of trials with dropped and repositioned objects is reduced. Over the course of the trial the object contact points would move towards unstable positions. Resetting the contact points allowed the subjects to restart their positions and properly continue with the trial. As we only look for the peaks in a trial, the repositioning, which usually took only 1-2 seconds, did not influence the results. The results directly relate to the stability of the grasp, where it appears that with added fingers subjects were more likely to keep a stable grasp on the object for extended periods of time. Potentially, in some cases the subject would lift only one finger at a time, resetting contact points. In applications, such as surgical robots, where the operator cannot remove the hand for a short period of time, it might be beneficial to use a 4 or 5 fingered grasp. In this case, the likelihood of losing control of the device is lowered. However, one needs to consider potential tradeoffs with the rotational range in the Y direction or with translational workspaces [10].

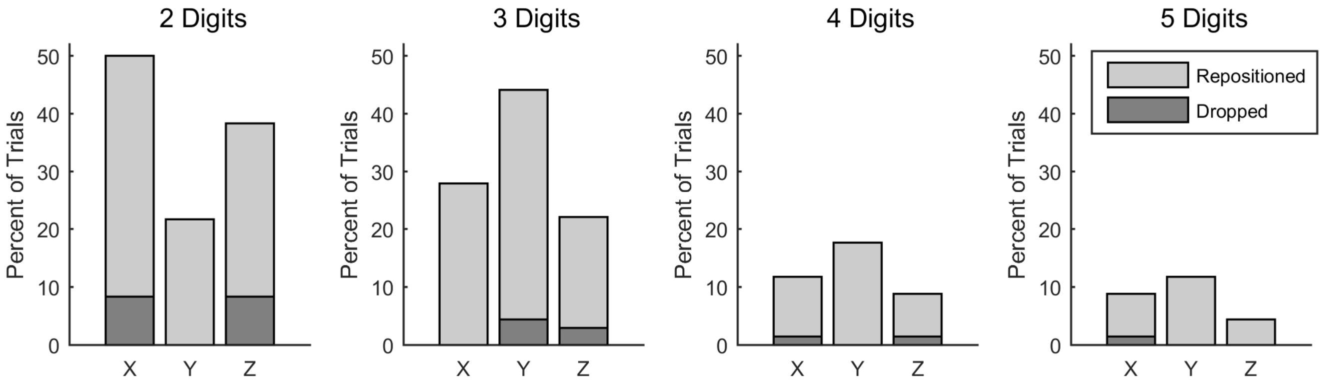

Figure 6. Statistics on dropping and repositioning the object during the trial. The data is based on the experimenter monitoring the trial and taking notes. “Dropped” indicates a trial, in which an object fell out of the hand of the subject at least once. “Repositioned” indicates a trial where the subject used their other (left) hand to hold the object, while the right hand opens and regrasps the object. In case dropping and repositioning was occurred, the trial is counted only as dropped.

Given that understanding rotations around particular axes may require a greater level of ‘technical’ background, subjects might have had different levels of comprehension of the task they were supposed to perform. Potentially, there may be some positive relationship between technical background and the ability to perform the tasks. Two subjects who achieved high rotation amplitudes were engineering students. This relationship is purely speculative, but might be worth to investigate further.

Currently, it is unclear if the three rotations studied are equally important for humans in everyday life. Certain rotations may be crucial for normal hand function, while others are less essential. We observed that the Y rotation, while having large rotation amplitudes, appeared to be less intuitive. Future research should explore the importance of specific rotation directions. We believe that this work helps to answer many specific questions about the capabilities of humans to rotate objects within their hand, which is useful in many domains, including artificial hand design, biomechanics and the design of haptic interfaces.

The analysis presented in this paper is a significant step toward understanding the rotational workspaces of human hands when manipulating objects with the fingertips, while keeping the contact locations constant. We plan to further analyze this data, extracting movement primitives of the fingertips and exploring virtual finger assignments. Furthermore, this one dimensional motions might be also a good basis to study muscle coordination patterns [20]. A future research direction is to find the axis of largest rotation amplitude, as we currently tested for three fixed axes.

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