A test of the mechanical advantage hypothesis during artificial reduction in thumb contribution to hold objects

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Abstract

Background.

Human hand plays a crucial role in accomplishing activities of daily living. In the human hand, the thumb has a critical role in grasp coordination. Without the thumb, it is not possible to hold an object stable. In this study, we investigated the nature of changes in fingertip forces in a multi-finger prehension task when the thumb rested on an unstable platform. We tested whether the mechanical advantage hypothesis holds true during the artificial reduction in thumb contribution to hold objects. We also computed the safety margin of the individual fingers and thumb.

Methodology.

Fifteen participants used five-finger prismatic precision grip to hold a custom-built handle with a vertical railing on the thumb side. A slider platform was placed on the railing such that the thumb sensor could move on either side in the vertical direction. There were two conditions. In the "Fixed" condition, the slider was mechanically fixed, and hence the thumb sensor could not move. In the "Free" condition, the slider platform on which the thumb was placed was made freely movable. In both conditions, the instruction was to grasp and hold the handle (and the platform) in static equilibrium. Tangential and normal forces were recorded from all fingers. The distribution of fingertip forces and moments changed depending on whether the thumb platform was movable (or not).

Results.

In the free condition, the drop in thumb tangential force was counteracted by increasing the normal force of the ring and little finger. We could also observe significantly comparable normal forces by the ring and little finger. The safety margin of the index and middle finger did not show a significant drop in free condition compared to fixed condition while the safety margin of ring and thumb increased significantly in free condition.

Conclusion.

We conclude that our results have falsified the mechanical advantage hypothesis. According to this hypothesis, little finger (one of the peripheral fingers) tends to exert significantly greater normal force in comparison to ring finger (one of the central fingers) during the moment production to compensate for the drop in thumb tangential force. On the contrary, little finger normal force did not show any significant change during the free condition compared to the ring finger normal force. Also, we found that the safety margin of the thumb and ring finger increased to prevent slipping of the thumb platform and to maintain the handle in static equilibrium during the free condition. Another essential point is that the rise in the safety margin of ring finger was not compensated by the significant drop in the safety margin of index and middle finger.

. **Keywords:** Thumb, prehension, safety margin, chain effects, mechanical advantage

Introduction

Many of our daily activities such as holding a pen or lifting a cup demand the use of our hand. These tasks require specific object orientation to enable better manipulation. Indeed, for successful manipulation of objects, it is always necessary to establish object stabilization. An object held in hand has to be maintained in static equilibrium for preventing tilt and slip. The evolution of the opposable thumb has endowed the human hand with the dexterity required for manipulating objects. The thumb is essential in grasping an object by using one of several grip configurations (Napier, 1956). Studies have been performed to examine the contribution of thumb during five finger pressing tasks (Olafsdottir, Zatsiorsky & Latash, 2005) and finger-thumb opposition movement tasks (Rachaveti et al., 2018). Studies have also focused on using a prehension handle to examine how the forces of fingers and thumb are controlled during grasping.

Fine coordination of normal and tangential force is a critical requirement for the handle stabilization. It is known that there will be a change in the finger normal force whenever there is a change in the tangential force (Cole & Abbs, 1988; Flanagan & Tresilian, 1994; Flanagan & Wing, 1993; Birznieks et al., 1998), frictional state at object-digit interface (Johansson & Westling, 1987; Burstedt, Edin & Johansson, 1997; Cadoret & Smith, 1996; Aoki et al., 2006), and external torque (Shim, Latash & Zatsiorsky, 2003). Depending on the tangential force changes, fingertip normal forces either increase or decrease. Modification of normal force to the tangential force adjustments can be controlled either by feed-forward or feedback mechanism. For stable grasping of an object, normal force exerted by the individual fingertips should be adjusted in such a way that it is neither too high to cause crushing of the object nor too low to cause dropping of the object. Grasp stability essentially implies slip prevention, tilt prevention, and resistance to perturbation (Zatsiorsky & Latash, 2008). Altogether, it is known that a proper scaling of normal force to changes in tangential force is critical for efficient grasping.

Studies on grasping have focused on the re-distribution of the individual fingertip forces and moments when there is a change in the object geometry (Zatsiorsky, Gao & Latash, 2006), orientation (Wu, Zatsiorsky & Latash, 2012), centre of mass (Santello & Soechting, 2000), external torque (Zatsiorsky, Gregory & Latash, 2002; Shim, Latash & Zatsiorsky, 2005a; Zatsiorsky, Gao & Latash, 2003b), thumb placement (Li et al., 1998; Zatsiorsky, Gao & Latash, 2003a) and frictional condition (Edin, Westling & Johansson, 1992; Aoki et al., 2006; Aoki, Latash & Zatsiorsky, 2007; McIsaac et al., 2009). These studies have reported that changes in task parameters cause a change in the distribution of tangential and normal forces of the individual fingers. In the study by Aoki et al., friction at the object-digit interface of the thumb and index finger side was altered to examine the force distribution (2006). Tangential forces on the smoother side were found to be lower compared to the rougher side, whereas the normal forces were modulated based on the frictional condition.

Multi-finger prehension is considered to be a redundant task that involves the generation of different patterns of the fingertip forces (Latash & Zatsiorsky, 2009). One common objective is to address how the central nervous system chooses a specific force pattern when changes

are induced to the five finger prehension handle held in static equilibrium. Five finger prehension stability was examined when a change was introduced to the entire width of the handle(Zatsiorsky, Gao & Latash, 2006) or individual digit width other than the thumb in horizontal (Slota, Latash & Zatsiorsky, 2012) and individual digit placement other than the thumb in vertical direction(Solnik, Zatsiorsky & Latash, 2014). When compared with other fingers in the human hand, the thumb makes a remarkable contribution to object stabilization. In some objects like a handheld portable radio, retractable ballpoint pens and certain models of pipette controller, a vertical tuner (or slider) is provided at the thumb side of the object to control the functionality. Such objects are operated by moving the vertical slider up or down using the thumb. Meanwhile, proper orientation and positioning of the object are also ensured for a stable grasp. The question of how object stabilization is achieved while grasping above mentioned objects has not been sufficiently addressed in the literature. Hence, in our study, slider was positioned on the thumb side of the handle (or object) rather than on a finger side.

Previous studies have shown that during pronation or supination moment production tasks to counter-balance the external torques imposed to the hand-held object, fingers with larger moment arms (i.e. index and little fingers) tend to produce a greater share of normal force compared to the fingers with the shorter moment arms (i.e. middle and ring fingers). This is called as the mechanical advantage hypothesis (Buchanan, Rovai & Rymer, 1989; Prilutsky, 2000; Shim, Latash & Zatsiorsky, 2005a; Zatsiorsky, Gregory & Latash, 2002). In our study, we hypothesized that the mechanical advantage hypothesis will continue to hold in the specific case when the thumb slider is made free to move vertically. Secondly, we hypothesized that the safety margin of the index and middle finger would drop when the thumb platform is free to slide in comparison to the thumb platform kept steadily fixed.

For a clear interpretation of the sequential local changes and to explain the cause-effect relationship in the individual fingertip forces, we employed the notion of chain effects (Shim, Latash & Zatsiorsky, 2003, 2005a; Zatsiorsky, Gao & Latash, 2003a; Zatsiorsky & Latash, 2004; Shim, Latash & Zatsiorsky, 2005b; Niu, Latash & Zatsiorsky, 2009; SKM et al., 2012). Chain effects refer to a sequence of local cause-effect adjustments which are necessitated either mechanically or choice made by the controller. Due to the removal of mechanical constraint at the thumb side, we expect that there will be a local change of a reduction in the thumb tangential force. This may be followed by a series of local changes in other fingers (a “synergic effect”).

Materials and Methods

Participants

Fifteen young healthy right-handed male volunteers (mean ± standard deviation Age: 25.6±2.7years, Height:172.6±3.9cm, Weight:73.3±9.6kg, Hand-length:18.6±0.9cm, Hand-width:8.7±0.3cm) participated in this experiment. Participants with any history of musculoskeletal or neurological illness were excluded.

Ethical Approval

The experimental procedures were approved by the Institutional ethics committee of IIT Madras (Approval number: IEC/2016/02/VSK-2/12. Full name of the committee that granted the approval: Institutional ethics committee of Indian Institute of Technology Madras). The experimental sessions were conducted in accordance with the procedures approved by the Institutional ethics committee of IIT Madras. Written informed consent was obtained from all participants before the start of the experiment.

Experimental Setup

We designed and built a vertically oriented prehension handle made of aluminium specifically for this study. The thumb side of this handle had a vertical railing. On this railing, we placed a slider platform such that it can move only in the vertical direction. The slider had a ball bearing, and hence the friction between the slider and the railing was minimal ($\mu \sim$ 0.001 to 0.002). We stored the handle in a dust free environment during non-use. Further, we regularly cleaned and lubricated the ball bearing between experimental sessions to ensure minimal friction. We used five 6-component force/torque sensors (Nano 17, Force resolution: 0.0125N, ATI Industrial Automation, NC, USA) to measure the fingertip forces and moments in the X, Y and Z directions. The thumb sensor was mounted on the slider platform. Hence the thumb sensor can freely move in the vertical direction, whereas the other finger sensors were fixed.

A laser displacement sensor (resolution,5µm; OADM 12U6460, Baumer, India) was mounted on a flat acrylic protrusion platform near the top of the handle on the thumb side. This sensor was used to measure the vertical displacement of the moving platform with respect to the geometric center of the handle. At the center of the handle frame, a thin horizontal solid line was drawn with a permanent marker to indicate the position at which the participants were required to maintain the slider in the free condition.

On top of the handle, an acrylic block extending in the anterior-posterior direction was placed. A spirit level with a bull's eye was placed on the participant side of the acrylic block. An electromagnetic tracking sensor (Resolution 1.27 microns, Static position accuracy 0.76mm, Static angular orientation accuracy 0.15º, Model: Liberty Standard sensor, Polhemus Inc., USA) was placed on the other side of the acrylic block as shown in Figure 1. Thirty analog signals from the force/torque sensors (5 sensors x 6 components) and single-channel analog laser displacement data were digitized using NI USB 6225 and 6002 at 16-bit resolution (National Instruments, Austin, TX, USA). This data was synchronized with six channels of processed, digital data from the electromagnetic tracker. The data were collected at 100 Hz.

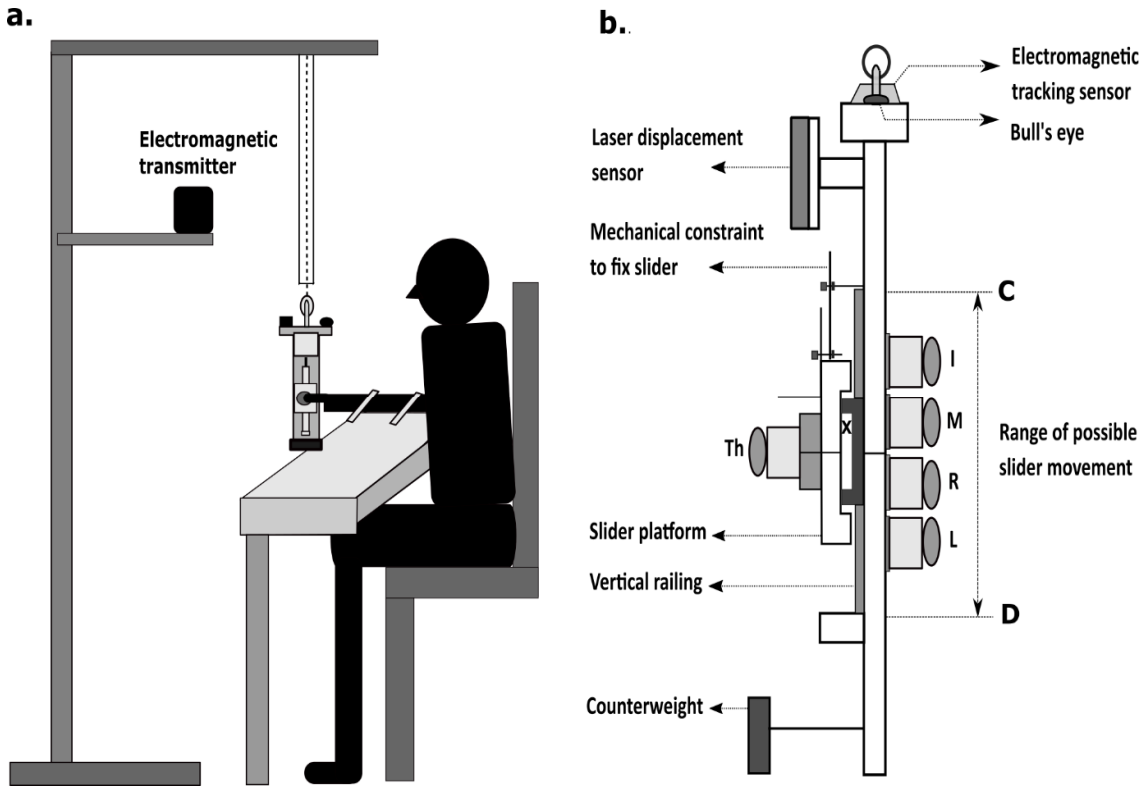

Figure 1 a. Schematic diagram of the subject holding the handle Thumb side of the handle is shown**.** The entire handle setup was suspended from a wooden frame using nylon rope passing through a hollow PVC pipe. The PVC pipe allowed slight movement of the rope (and handle) but not undesirable large amplitude movement of the handle. The participant was required to lift the handle from its suspended position by 2cm vertically, thus causing a slack of the nylon rope during the trial recording**.** The transmitter of the electromagnetic tracking system was placed few cm away from the handle to avoid distortion**. b. Schematic diagram of the experimental setup** ATI Nano 17 force sensors mounted on the handle frame (20cmx1cmx3cm) to measure the forces of fingers (I-Index, M-Middle, R-Ring, Little-L, Th-Thumb). The geometric centre of the handle is represented by the symbol '**X** on the slider. The centres of the force sensors (excluding the thumb) were placed at a distance 2cm apart from each other. Two solid horizontal lines were drawn (one on the slider and the other on the handle frame between middle and ring fingers). In free condition, slider platform can translate over vertical railing such that it can theoretically move from point C to point D. The maximum possible vertical displacement of the slider platform and hence the thumb sensor was 7cm. The horizontal distance between the grasping surfaces of the thumb and finger sensors was 6.5cm. We covered the surface of all the force sensors with 100 grit sandpaper. Mass of the slider platform was 0.101kg. The mass of the entire handle including the slider was 0.535kg. To bring the whole object center of mass close to the geometric center of the handle, a rectangular aluminium counter-weight of 0.035kg was placed close to the bottom, on the thumb side of the handle

Experimental Procedure

Participants washed their hands with mild soap and water before the beginning of the experiment. Friction experiment was performed first followed by the Prehension experiment.

Friction experiment

We designed a device that consists of a six-component force/torque sensor (Nano 25, ATI Industrial Automation, Garner, N.C) mounted on the top of the aluminium platform. The platform moved linearly with the help of timing belt-pulley system powered by a servomotor (Savescu, Latash & Zatsiorsky, 2008; Park et al., 2014). A customized LabVIEW program was written for the data collection and to control the operation of the motor. Forearm and wrist movements of the participants were arrested by Velcro straps while a wooden block was placed underneath the participant's palm for the steady hand and finger configuration. Participants were instructed to produce a constant downward normal force of 6N for 3s to initiate movement of the servomotor. Visual feedback of the normal force was shown on the computer monitor for the participant. The platform moved at a speed of 6mm/s away from the participant. Data was collected from the index and thumb finger only. One trial per finger was conducted. Friction coefficient was computed by dividing the tangential force and normal force at the time of slip.

Prehension experiment

Participants were seated comfortably on a wooden chair with their forearm resting on the table. The right upper arm was abducted approximately 45º in the frontal plane, flexed 45º in the sagittal plane with the elbow flexed approximately about 90º. To have a natural grasping position, the forearm was supinated to 90º. The movements of the forearm and wrist were restricted by strapping them to the tabletop with Velcro.

The experiment involved a task that had two different conditions: "fixed" and "free". In the fixed condition, the vertical thumb slider was fastened securely using a mechanical constraint. This fixed position was such that the horizontal line passing through the center of the thumb sensor was precisely aligned with the solid horizontal line drawn at the center of the handle (i.e., found between the center of the middle and ring finger sensors). In the free condition, this mechanical constraint was released such that the slider was free to vertically translate over the entire length of the vertical railing. Theoretically, the thumb sensor could move a maximum range of 7cm, approximately between the index finger and little finger. However, in the current study, we required the thumb platform to be maintained between middle and ring fingers. This was in addition to the requirement to maintain the handle in static equilibrium. A spirit level with a bull's eye provided tilt feedback to the participant.

In both conditions, the task was to lift the handle vertically upward from the suspended position with their right hand to support the load of the handle with the fingers and thumb. The handle was required to be held in such a way that the fingertips' center approximately coincided with the center of each sensor. Eight participants performed free condition first followed by the fixed condition. The other seven participants performed fixed condition first

followed by the free condition. The experimenter (but not the participant) could view the normal force of all fingers, slider's vertical displacement data, position and orientation of the handle. The trial started only after the participant held the handle in a stable manner and informed the experimenter to start. The participants were instructed to grasp and hold the handle vertical by maintaining the bubble in the bull's eye to the center throughout the trial. They were also instructed to lift the handle with all fingers in both conditions and position the horizontal line on the thumb platform matching the horizontal line drawn midline between the middle and ring finger in free condition.

Five familiarization trials (not included in the analysis) were provided at the start of each condition. Each experimental condition was conducted in a separate session. A rest period of one hour was provided between conditions. In each condition, 30 trials were recorded. Each trial lasted for 10s with a minimum mandatory break period of 30 seconds between the trials. Additional rest was provided when the participants requested.

Data Analysis

The data were collected using a customized LabVIEW (LabVIEW Version 12.0, National Instruments) program and offline analysis was performed in Matlab (Version R2016b, MathWorks, USA). Force/Torque data were low-pass filtered at 15Hz using second-order, zero phase lag Butterworth filter. We only considered the data between 2.5 and 7.5s (500 samples) for all the analyses to eliminate the start and end of trial effects.

% Change in Normal and Tangential forces

Although some participants performed the "free" condition first, since we used fixed condition as control, we computed % change with respect to "fixed" condition regardless of the order in which the conditions were performed. The % Change in force was computed using the following equation.

$$\%\ \text{Change in Normal force (NF)} = \frac{(\text{Average NF in free condition} - \text{Average NF in fixed condition})}{\text{Average NF in fixed condition}} * 100$$

(1)

Likewise, % Change in tangential force was also computed.

Normal force sharing in percentage

Normal force sharing of the individual fingers was expressed in terms percentage by taking the average across 500 samples of each trial, then averaged across all trials and participants.

Safety Margin

Safety margin (SM) is the amount of extra normal force applied in addition to the minimally required normal force to avoid slipping of the handle. We computed SM for all fingers using the following equation (Burstedt, Flanagan & Johansson, 1999; Pataky, Latash & Zatsiorsky, 2004; SKM et al., 2012).

$$SM(t) = \frac{\left[F_n - \frac{|F_t|}{\mu}\right]}{F_n}$$

(2)

where μ is the coefficient of friction between the finger pad and sandpaper, t refers to the time course of 5s, F_n is the normal force and F_t is the tangential force applied to the object. SM was calculated with the corresponding friction coefficient value μ of each participant that was computed from the friction experiment data. The average friction coefficient of index and thumb computed across 15 participants are 0.9689±0.0054 and 0.9745±0.0109. For statistical analysis, Fisher's Z-transformed SM values were found by using the following equation.

$$SM_z = 0.5 * ln\left(\frac{1+SM}{1-SM}\right)$$

(3)

Linear discriminant analysis

To examine how the change in tangential force produced by the thumb affected the moments produced by normal forces and hence, the static equilibrium of the object, we used Linear discriminant analysis (LDA). LDA was performed separately between the following pairs of variables:

F_t^{Th} & M_n^{VF}

F_t^{Th} & M_n^{R}

F_t^{Th} & M_n^{L}

F_t^{Th} & $(M_n^{R} + M_n^{L})$.

Linear discriminant classifier was trained with the set of data points on thumb tangential force and the moments mentioned above for the two conditions. We performed this analysis for the four pairs of variables mentioned above (see supplementary Figure S3, Figure S4, Figure S5). For brevity, only the results from F_t^{Th} & M_n^{VF} are presented, since the other results were similar.

Statistics

Statistical analyses were performed using R. Two-way repeated measures ANOVA were performed with the condition (2 Levels: Fixed and Free) X finger (5 Levels: Index, Middle, Ring, Little and Thumb) as factors for normal force, tangential force, z-transformed normal force sharing and safety margin. Sphericity test was performed on the data for all cases, and the number of degrees of freedom was adjusted using the Huynh-Feldt (H-F) criterion wherever required. Post-hoc pair-wise comparisons was performed using Tukey test to explore the significance within the factors. We also performed an equivalence test using the two one-sided t-test (TOST) approach (Lakens, 2017), to check for equivalence of the tilt angles and safety margin between fixed and free conditions.

Results

Task performance

Ideal performance of the task in both fixed and free condition would be to hold the object in static equilibrium. In the free condition, participants were also required to align the horizontal line on the slider to the horizontal line on the handle frame. Figure 2 (left and right column) shows the time profiles of average normal force and average tangential force in the fixed and free condition. Note that the standard error of means of the normal and tangential force of the individual fingers (excluding the thumb) in the free condition was found to be greater when compared to the fixed condition.

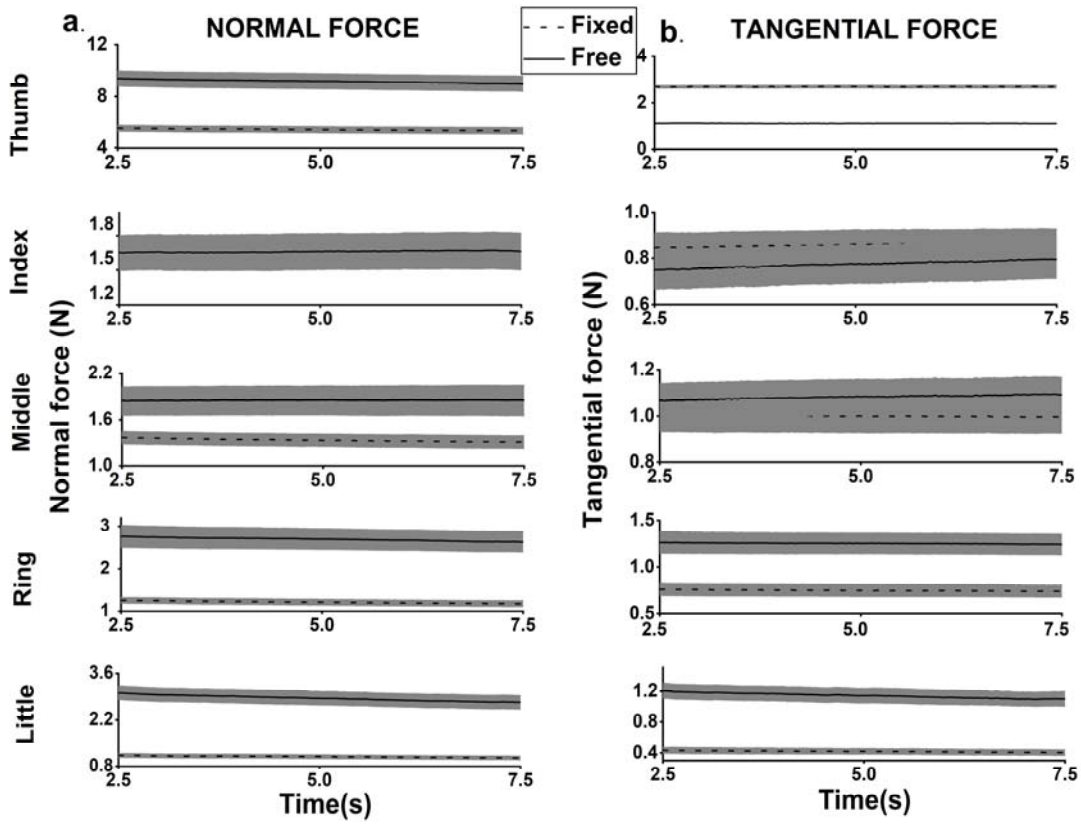

Figure 2 a. Average time profile of Normal force b. Average time profile of Tangential force of all the fingers during fixed and free conditions Data shown are averages across subjects & trials in each condition. Fixed condition is represented with dashed lines and free condition represented with solid line. Thick lines and shaded areas refer to the means and standard error of means.

The average net rotation of the handle in the fixed and free condition was 4.13º and 3.83º, respectively. The tilt angles were not significantly different. They were also statistically equivalent as per the equivalence test according to the two one-sided t-test (TOST) procedure(Lakens, 2017). The amount of deviation of the thumb sensor center from the marked position on the handle frame was calculated by finding the absolute difference between the maximum and minimum values of the laser displacement data within each trial.

This difference was computed for all trials, averaged, and then averaged across participants. On an average, during the free condition deviation of the marked horizontal line on the slider from the horizontal line on the handle was 0.88±0.06 mm.

Changes in Normal force and tangential force in the thumb and other fingers

Normal force produced by the index finger was found to be non-different in both fixed and free condition, and hence the index finger normal force data were found overlapping in Figure 2(a). The average normal force of middle, ring, little and thumb in free condition was significantly higher than the fixed condition. The average thumb tangential force in the free condition decreased significantly compared to the fixed condition. This decrease in the thumb tangential force was compensated by the increase in the tangential force and normal force of ring and little finger to maintain the handle in static equilibrium during the free condition. Figures 3(a) and 3(b) show averages (across time, trials, and participants) of normal force and tangential force.

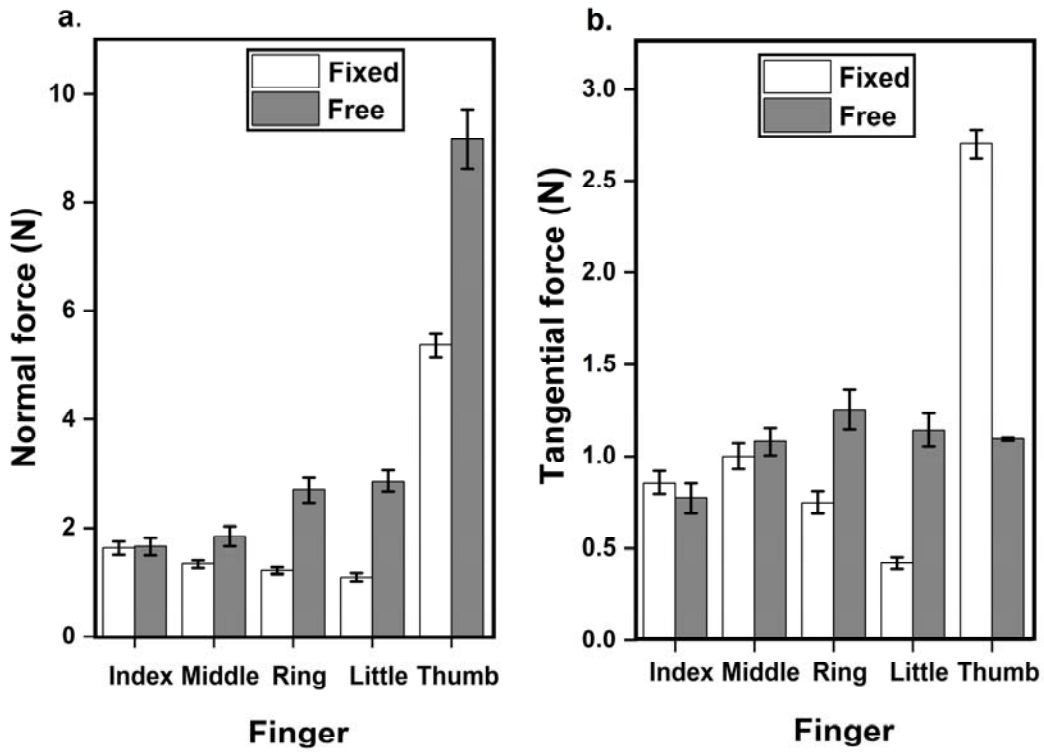

Figure 3. Average of Normal Force and Tangential force of all fingers at different conditions a. Average Normal force of Index, Middle, Ring, Little and Thumb in fixed and free condition. Normal force of middle, ring, little and thumb fingers in free condition significantly increased ($p<0.001$) compared to fixed condition. b. Average Tangential force of Index, Middle, Ring, Little and Thumb in fixed and free condition. Thumb tangential force in free condition significantly decreased ($p<0.001$) compared to fixed condition. Ring and little finger tangential force in free condition significantly increased ($p<0.001$) compared to fixed condition. The columns and errorbars indicate means and standard error of means.

A two-way repeated-measures ANOVA on average normal force with factors condition and finger showed a significant main effect of condition ($F_{(0.76,10.64)}=85.44; p<0.001$, $\eta^2_p=0.85$) corresponding to a significantly higher ($p<0.001$) normal force in free condition compared to fixed condition. There was a significant main effect of the finger ($F_{(2.24,31.36)}=259.23; p<0.001$, $\eta^2_p=0.94$) corresponding to a significantly higher ($p<0.001$) normal force for thumb than other fingers. To check for differences between fingers other than the thumb, we performed a one way ANOVA. However, we did not find any such differences in normal force of individual fingers other than the thumb. The interaction condition x finger was significant ($F_{(3.04,42.56)}=56.70; p<0.001$, $\eta^2_p=0.80$) reflecting the fact that the average normal force of thumb in free and fixed condition(9.16N & 5.36N) was significantly higher than the other fingers index(1.65N &1.63N), middle(1.84N &1.33N),ring(2.69N&1.21N) and little(2.86N & 1.09N).

The effects of condition on average tangential force were significant ($F_{(0.91,12.74)}=13.44; p<0.01$, $\eta^2_p=0.5$) according to two-way repeated-measures ANOVA. A significant main effect was found for finger ($F_{(3.8,53.2)}=46.87; p<0.001$, $\eta^2_p=0.77$). This indicated that the thumb tangential force was different from other fingers. Pairwise comparisons showed that the tangential force of the ring and little finger increased significantly ($p<0.001$) in free condition (1.25N, 1.14N) compared to fixed condition (0.74N, 0.41N). Interaction effects were significant ($F_{(3.64,50.96)}=127.54; p<0.001$, $\eta^2_p=0.90$) for condition x finger reflecting the fact that the average thumb tangential force decreased significantly ($p<0.001$) in free condition(1.09N) compared to fixed condition(2.70N).

Percentage change in the normal and tangential forces

We observed a 60% drop in the tangential force of the thumb. This drop was compensated by 70% and 199% rise in the tangential force of the ring and little finger in free condition with respect to fixed condition. In addition, there was a simultaneous increase in the normal force of the same fingers by 121 % and 170%. The rise in the normal force of ulnar fingers was balanced by increasing the normal force of the thumb by 70% (see Figure 4).

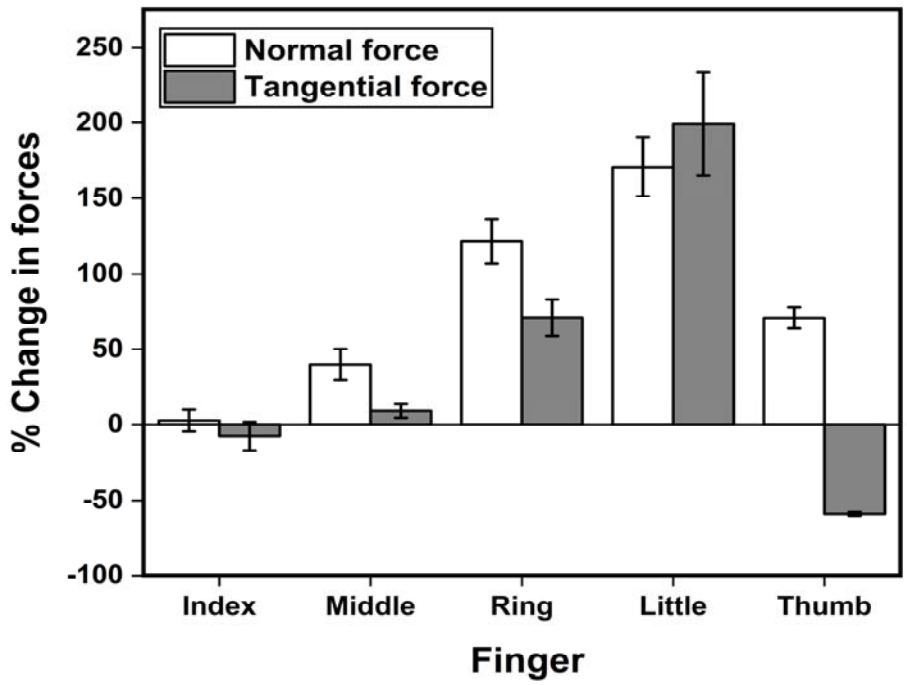

Figure 4. Percentage change in the Normal and Tangential forces Normal force is represented in white and the Tangential force is represented in grey. All changes are computed for the free condition compared to the fixed condition. Normal force of the middle, ring, little and thumb increased by 40%, 121%, 170% and 70% respectively. Tangential force of the middle, ring and little fingers increased by 9%,70% and 199% respectively. The ring and little finger forces increased much more than the middle and index finger. Note that the thumb tangential force decreased by 60%, the normal force increased by around 70%.

Force sharing of the normal forces

Normal force sharing was different between the two conditions. We observed a significant main effect of condition ($F_{(1,14)}$=13.83;p<0.01, η^2_p=1.06) on the normal force sharing of the individual fingers other than the thumb. The percentage share of the ring (p<0.05) and little finger (p<0.001) normal force was significantly higher in free condition compared to the fixed condition while the index (p<0.001) and middle (p<0.05) finger contributed significantly lesser normal force share in free condition compared to the fixed condition (see Figure 5)**.**

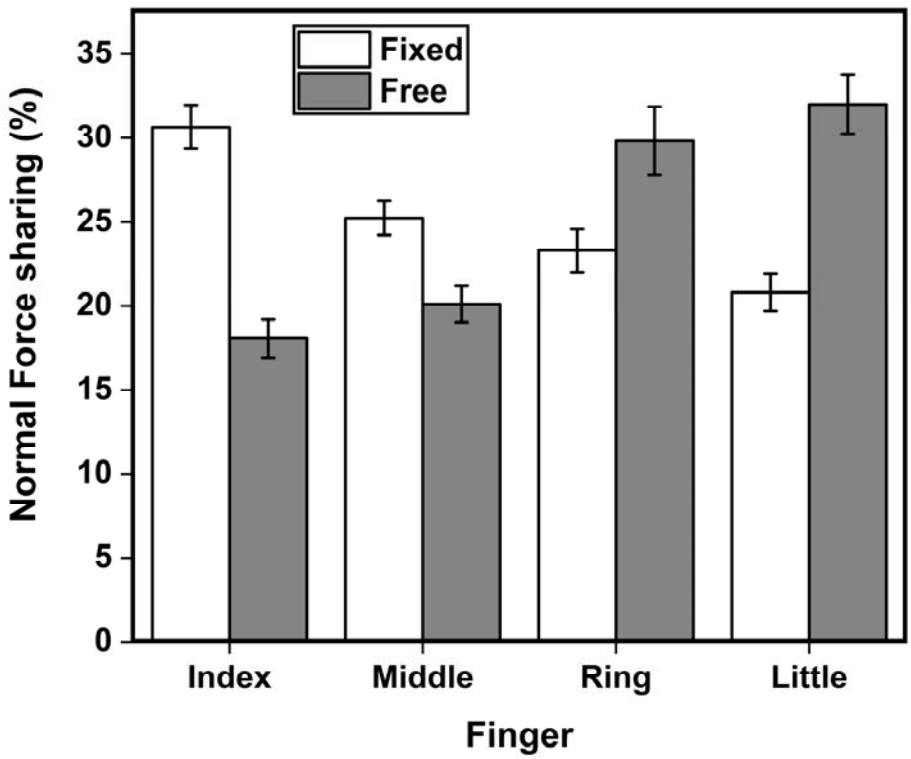

Figure 5. Normal force sharing in % Normal force share of the individual fingers apart from thumb for the fixed (white) and free (grey) condition is expressed in the form of percentage. In the free condition, normal force share of the ring ($p<0.05$) and little ($p<0.001$) finger significantly increased compared to fixed condition. Index ($p<0.001$) and middle ($p<0.05$) finger showed reduction in the normal force share in free condition in comparison to the fixed condition.

Changes in Safety Margin due to condition and fingers

Safety margin changed between the two conditions. A two-way repeated-measures ANOVA was performed using the factors condition and finger. Both factors, condition ($F_{(0.89,12.46)}=50.40; p<0.001, \eta^2_p=0.78$) and fingers ($F_{(3.44,48.16)}=29.26; p<0.001, \eta^2_p=0.67$) showed statistical significance. Post-hoc pairwise comparisons showed significantly higher SM_z for ring finger ($p<0.05$) and thumb ($p<0.001$) in free condition when compared to fixed condition. Interaction effect also showed statistically significant difference ($F_{(3.56,49.84)}=66.11; p<0.001, \eta^2_p=0.82$) for the safety margin between the factors such as condition and fingers. In addition to this, the safety margin of index, middle and little fingers in fixed condition were found to be equivalent to the safety margin of the respective fingers in free condition. These findings are illustrated in Figure 6

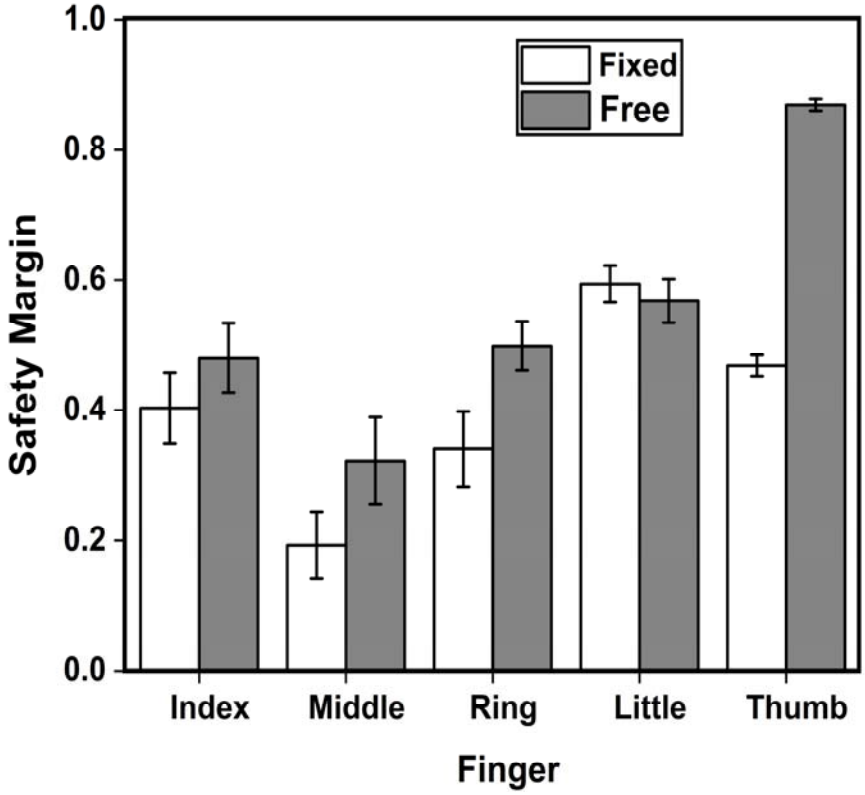

Figure 6. Safety Margin of individual fingers and thumb in fixed and free conditions Safety margin of thumb ($p<0.001$) and ring ($p<0.05$) finger in free condition significantly increased compared to the fixed condition. Safety margin of the index, middle and little fingers in free condition were found to be equivalent to the safety margin of the corresponding fingers in free condition.

Linear Discriminant Analysis - Classification accuracy

We investigated the change in the moment due to normal force due to the change in the tangential force of the thumb during the fixed and free conditions using linear discriminant analysis (LDA). The change in thumb tangential force resulted in the change in the normal force of the other fingers which in turn caused the change in the moment due to the normal force (see supplementary note on the moment computation). The two different conditions: fixed and free were considered to be the two different classes for the purpose of LDA. Both the classes were found to be linearly separable by a decision boundary that was constructed using LDA. The classifier was trained with 405 data points on thumb tangential force and moment due to normal forces of the respective fingers. LDA was able to predict the test data at an accuracy of 98%, sensitivity 100%, specificity and precision 97%, false-positive rate of 2% for all four cases. This result is illustrated in Figure 7. The results for the other pairs of variables are included in the supplementary Figure S3, Figure S4, Figure S5.

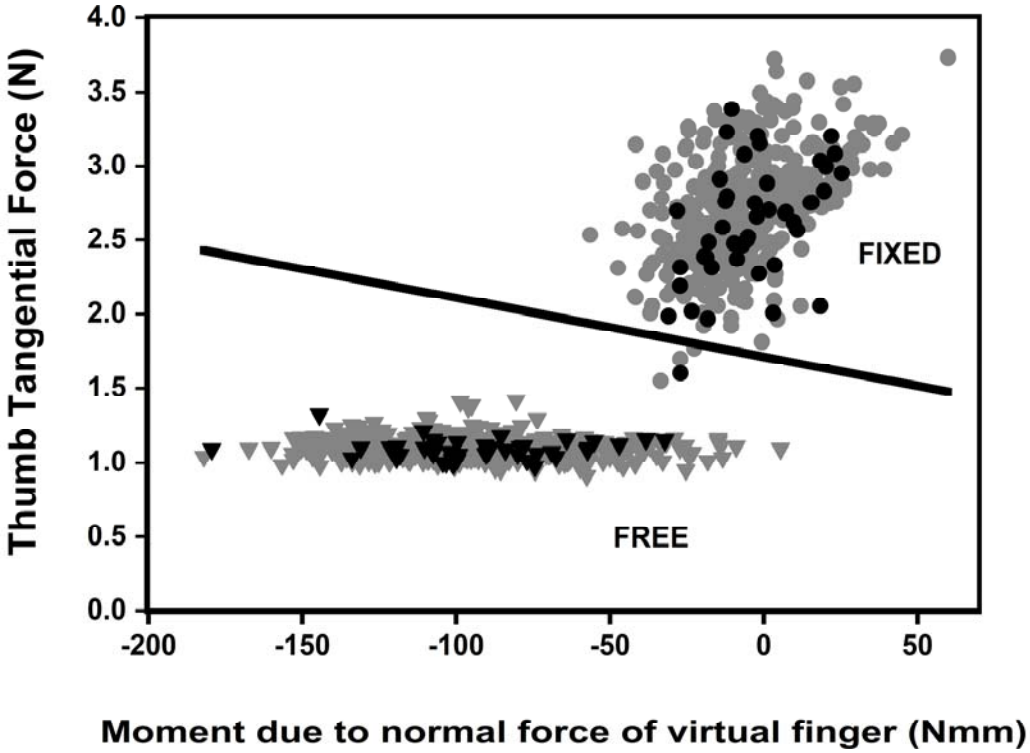

Figure 7. Thumb tangential force (F_t^{Th}) as a function of Moment due to normal force of Virtual Finger (M_n^{VF}) Each datapoint in the scatter plot represents time average of a single trial of a single subject. Data from all subjects are presented. Inverted triangle in grey & black colours are train (405) and test (45) datapoints in free condition. Circles in grey & black colours are train (405) and test (45) datapoints in fixed condition. Note: Only one test datapoint belonging to fixed condition was wrongly classified as free condition, so the accuracy of classification is 98%, sensitivity is 100%, specificity and precision is 97%, false positive rate is 2%.

Discussion

In our study, participants attempted to maintain the handle in static equilibrium both during the fixed and free conditions. In the fixed condition, when the mechanical constraint was used to restrict the translation of the thumb vertically, the entire load of the handle was shared by the thumb and other fingers. In free condition, the thumb platform was made free to slide over the railing on the handle. The changes in friction that occurred in the surface between the thumb platform and handle can be perceived by the proprioreceptors located in the thumb muscles and joints. This sensory information is communicated to the CNS via the afferent path. In response to that, CNS generates a motor command to the thenar muscles controlling the thumb. The thumb has only to support the slider platform whose weight is around 1N and hence there was a drop in tangential force from ~ 2.7N to 1N. If the participant attempts to increase the tangential force above 1N, the thumb platform would slide upwards (violation of experimental instruction).

Drop in thumb tangential force caused an increase in the tangential force of virtual finger to overcome the weight of the handle. The tangential force of the virtual finger was ~ 4.24N which was three times greater than the tangential force of the thumb (1.09N). This, in turn, could cause a tilt of the handle in the counter-clockwise direction. Such a tilt would disturb the rotational equilibrium of the handle. Eventually, there was a compensatory adjustment in the normal and tangential forces of index, middle, ring and little finger to retain the handle equilibrium. According to the mechanical advantage hypothesis, peripheral fingers (index and little) that have larger moment arms (for normal force) tend to produce greater normal force compared to the central fingers (middle and ring) having shorter moment arms during moment production tasks. Earlier, this hypothesis was tested in the pronation or supination moment production tasks to establish static stabilization of the handle when external torques introduced to the handle. From their results (Slota, Latash & Zatsiorsky, 2012; Zhang et al., 2009), it was found that the peripheral fingers exert greater normal force. In our study, the applicability of the mechanical advantage hypothesis was examined to check whether the little finger (one among the peripheral fingers) produces a larger normal force compared to the ring finger (having shorter moment arm) to overcome the drop in thumb tangential force. As mentioned earlier, the drop in the thumb tangential force could cause tilt of the handle in the counter-clockwise direction. To overcome that, clockwise tilt (or supination moment) has to be produced by the normal forces of the ring and little finger. Hence we expected that the little finger would produce greater normal force than the ring finger causing supination moment in-order to bring the handle back to its equilibrium state.

However, we observed that both the ulnar fingers exerted a statistically equivalent absolute normal force (in Newton) and normal force sharing (in terms of %). The results of our current study are not in agreement with the mechanical advantage hypothesis as the ulnar fingers exerted comparable normal forces. This might be due to the lesser mass of the handle when compared to the studies (Shim, Latash & Zatsiorsky, 2005a; Gao, Latash & Zatsiorsky, 2006) which found support for the mechanical advantage hypothesis. Further, in other studies (Shim, Latash & Zatsiorsky, 2005a; Zatsiorsky, Gregory & Latash, 2002), external torques imposed to the handle was in the range of Newton-meter (Nm) while in our study counter-clockwise tilt caused due to the drop in the thumb tangential force was in the range of Newton-centimeter (Ncm) which is comparatively lesser. Also, not all the results of a study on finger coordination during the moment production on a mechanically fixed object (Shim, Latash & Zatsiorsky, 2004) supported the mechanical advantage hypothesis. One common point between our study and Shim et al (2004) study was that moment was produced by the fingers. But, these moments were not exerted to compensate for the torques caused due to the addition of external load introduced to the handle.

The central nervous system probably has chosen to increase tangential forces of ulnar fingers, naturally accompanied by an increase in their normal forces. The increase in normal forces of ulnar fingers would disturb the horizontal equilibrium of the handle (see Figure 8). Consequently, thumb normal force increased to 9N (almost doubled compared to thumb normal force in fixed condition). This helped to balance the forces in the horizontal direction and also to avoid slipping of the thumb slider downwards (Burstedt, Edin & Johansson, 1997). Slips are more likely to occur on the surface of low friction such as the one used in our slider. Hence, we believe that the normal force of the thumb increased in a “feed-forward”

manner. A ‘non-slip strategy’ (Edin, Westling & Johansson, 1992) for the thumb by raising the safety margin of the thumb (see Figure 6) when there was a vertical unsteadiness at the slider platform was chosen by the system. In contrast, if the normal forces of the thumb remain the same or decrease, there will be an increase in the clockwise moment caused due to the ulnar fingers. This would result in the rotation of the handle in the clockwise direction (see supplementary Figure S1). We further examined whether there is any shift in center of pressure (COP) of the fingers and thumb in the vertical direction to compensate the tangential force drop in the thumb. So, we performed planned pairwise comparison on the difference in COP shift from the initial to final point between the conditions and found that there was not any significant difference in all the fingers and thumb.

By definition, safety margin is meant to be the amount of extra normal force applied to avoid slipping. From the results of our study, we could observe a significant increase in the safety margin of ring finger as there was a rise in the normal force of ring finger to compensate the drop in the tangential force of the thumb. It is known that the tangential force of the virtual finger increase to compensate for the drop in the tangential force of the thumb in order to balance the vertical equilibrium of the handle. Prior studies (Radwin et al., 1992; Kinoshita, Murase & Bandou, 1996; Zatsiorsky, Li & Latash, 1998; Aoki, Francis & Kinoshita, 2003) have shown that the index and middle fingers play a major role in producing greater force compared to the ring and little finger. Next to the thumb, the index finger is considered to contribute in a great way for the independent force control (Jones & Kamper, 2018). Meanwhile, the middle finger (one among the central finger) was responsible for supporting the weight of the handle (Zatsiorsky, Gregory & Latash, 2002). Therefore, we speculated that the index and middle finger share a greater tangential force compared to the ring and little finger during the multi-finger prehension task. However, it cannot be accompanied by the greater share of normal forces as it could cause further tilt in the counter-clockwise direction. Hence, we expected that there would be a drop in the normal force of index and middle finger in free condition. According to our second hypothesis, there will be a significant drop in the safety margin of index and middle finger during the free condition compared to fixed condition. Contrary to our expectations, safety margin of index and middle finger showed no statistical difference between the fixed and free conditions. Hence, our findings were not in agreement with the second hypothesis as well.

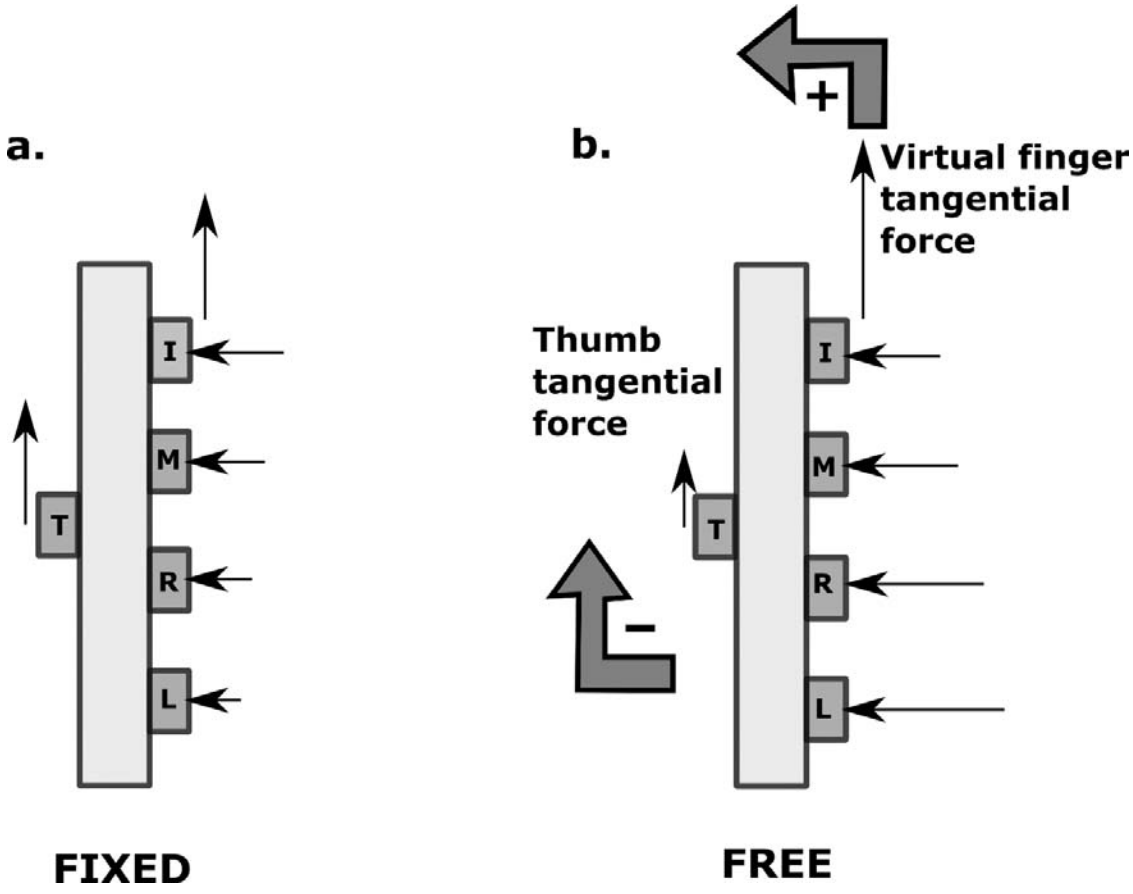

Figure 8. Force and Moment distribution pattern in fixed and free condition The length of the arrow corresponds to the absolute magnitude of the force. In fixed condition, moment due normal force of virtual finger ( ) is approximately zero and moment due to normal force of thumb ( ) is minimal so both are not represented. Note the magnitude of virtual finger tangential force and thumb tangential force remained almost same in fixed condition. In free condition, '+' sign indicates anti-clockwise moment and '-' sign indicates clockwise moment. Decrease in the tangential force of thumb and increase in the virtual finger tangential force are shown

Due to the unsteady thumb platform, cutaneous receptors on the thumb (in addition to proprioceptive input) detect the frictional change. The CNS, in turn, responds by necessitating the mechanical action of lowering tangential force of the thumb. The magnitude of thumb tangential force in free condition depended on the mass of the thumb platform. We consider this to be the first local change which initiated the synergic effect in the ring and little finger. In our current study the following chain effects were observed during the free condition: mechanical constraint to fix the thumb in position was removed→ tangential force of the thumb decreases → VF tangential force increases → rise in the counter-clockwise moment → compensated by the increase in the normal force of ring and little finger → moment due to normal force of ring and little finger increases in the clockwise direction to

counterbalance the rise in counter-clockwise moment → increase in normal force of ring and little finger was compensated by the increase in the thumb normal force. Thus, the change in the tangential force of the thumb resulted in the re-arrangement of normal force of all the fingers. This is evident from Figure 4 where we observe an increase in the percentage change in the normal forces of all the fingers and thumb in free condition compared to the fixed condition. On the other hand, the percentage change in the tangential force of thumb decreased in free condition. Local change of drop-in thumb tangential force results in the tilting of the handle in the counter-clockwise direction (Niu, Latash & Zatsiorsky, 2007). Meanwhile, synergic change of increasing the normal forces of the ulnar fingers brings about a compensatory tilt in the opposite direction which helps the handle to retain its rotational equilibrium. The normal and tangential force adjustment at thumb was primarily due to a choice made by the controller driven by task mechanics and task instruction.

In free condition, data is spread wider across various values of moments due to variations in normal force of virtual finger (see Figure 7). Though there was a constant moment arm of normal force for virtual finger in free condition, moments varied widely because of the change in the normal force of ring and little finger. Moment due to normal force of little finger was greater than the moment due to normal force of ring finger as the little finger ('peripheral finger') is among the moment generating fingers (Zatsiorsky, Gregory & Latash, 2002). In fixed condition, the thumb tangential force was spread in the shape of a vertical ellipse (in Figure 7). Tangential force of the thumb was found to be denser at approximately 2.7N and sparsely distributed between 2N to 3.5N. Moment due to normal force of VF was denser around 0Nmm. But the moment due to the normal force of ring, little fingers and sum of the ring & little fingers was negative suggestive of a 'clockwise moment'.

Concluding comments

When the thumb undergoes a local change of decreasing the thumb tangential force, handle equilibrium is disturbed. Subsequently, the handle equilibrium was restored by increasing the normal force of ring and little finger. It was evident from our current study that the ring and little finger normal force showed statistically comparable increase to counteract the drop in the thumb tangential force. Thus, the little finger (one of the peripheral fingers) did not produce greater share of normal force (falsified mechanical advantage hypothesis) than ring finger to cause supination moment for balancing drop in thumb tangential force. In addition to this, there was no statistical difference in the safety margin of index and middle finger in free condition compared to the fixed condition. The results of this study can serve as an input towards development of robotic hands that involve operating hand tools that require vertical motion of the thumb for the operation. Our future studies shall focus on examining the fingertip force re-distribution in all the fingers when the thumb is either moved up or down (towards middle or ring finger) by mounting it on the unsteady platform.

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SUPPLEMENTARY INFORMATION

Supplementary Note on the Moment computation

The unsteady thumb platform caused fingertip force re-distribution. Due to the re-distribution of fingertip forces, there was a change in the moment contribution of each finger. We computed moment due to virtual finger normal force M_n^{VF}, the moment due to thumb tangential force M_t^{Th}, the moment due to normal force of the ring (M_n^R) & the little (M_n^L) fingers, sum of the moment due to normal force of ring and little finger ($M_n^R + M_n^L$) and total moment made by the virtual finger M_{tot}^{VF} (see Supplementary Equation S6)

Moments Computation:

For an object in static equilibrium, we computed moments by various forces involved as described in previous studies (Zatsiorsky et al. 2003). Moment due to normal force of all fingers was calculated by,

$$M_n^j = \left(d^j + COP_y^j\right)F_n^j \qquad \text{(Supplementary Equation S1)}$$

$$COP_y = \frac{M_x}{F_n} \qquad \text{(Supplementary Equation S2)}$$

Moment due to the normal force of the Virtual Finger was calculated by

$$M_n^I + M_n^M + M_n^R + M_n^L = M_n^{VF} \qquad \text{(Supplementary Equation S3)}$$

Moment due to thumb tangential force,

$$M_t^{Th} = -r^{Th}F_t^{Th} \qquad \text{(Supplementary Equation S4)}$$

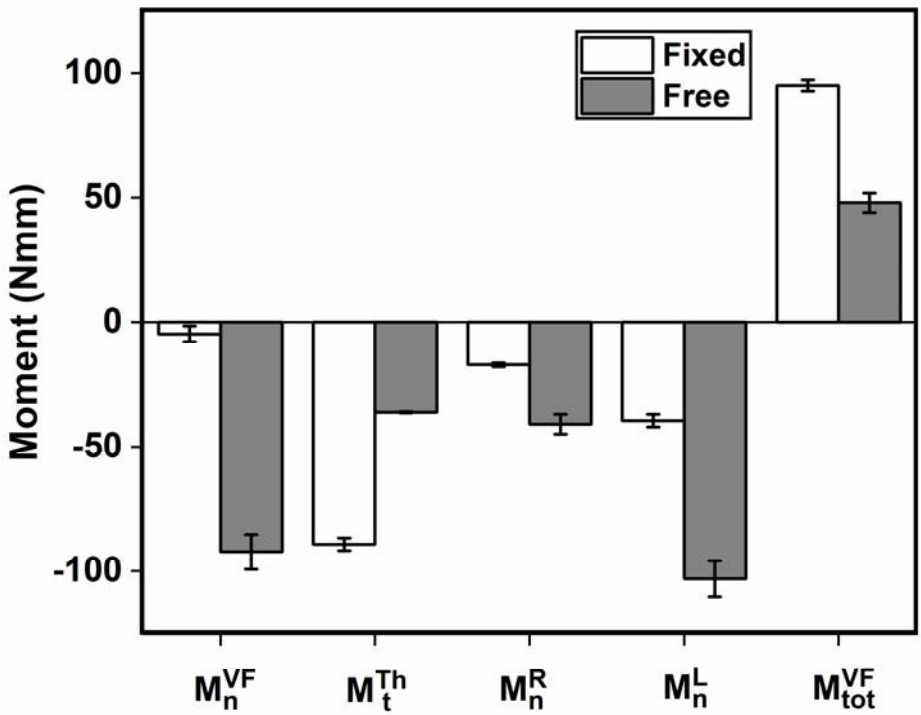
Total Moment due to virtual finger is the sum of the Moment due to the normal and tangential force of virtual finger.

$$M_t^I + M_t^M + M_t^R + M_t^L = M_t^{VF} \qquad \text{(Supplementary Equation S5)}$$

$$M_n^{VF} + M_t^{VF} = \text{Total Moment } (M_{tot}^{VF}) \qquad \text{(Supplementary Equation S6)}$$

j=Index(I), Middle(M), Ring(R), Little(L) or Thumb (Th). COP_y refers to the center of pressure on the sensor surface about Y-axis (Zatsiorsky, Gao & Latash, 2003; Aoki et al., 2006). M_x refers to moment about the X-axis, n and t represent normal and tangential forces. d is the vertical distance from the geometric center of the handle to the center of a finger sensor. r refers to tangential moment arm (horizontal distance from the centre of the handle to the point of force application on the finger sensor).

In the fixed condition, d^{Th} is a constant. Hence, M_n^{Th} varies only due to changes in F_n^{Th}. Note that in the case of free condition, both d^{Th} & F_n^{Th} are quantities that can vary at each point in time since the thumb sensor can be displaced vertically. The thumb tangential force is expected to produce a clockwise moment. The computed moments were averaged across the time, trials and participants.



Supplementary Figure S1. Average Moment in fixed and free condition Moment due to normal force of Virtual finger (M_n^{VF}), Moment due to tangential force of thumb (M_t^{Th}), Moment due to normal force of ring finger (M_n^{R}), Moment due to normal force of little finger (M_n^{L}) and Total moment due to Virtual finger (M_{tot}^{VF}) in fixed and free condition have been presented. In all cases, the moments between the two conditions are significantly different ($p<0.001$). Note the increase in M_n^{VF} (in clockwise direction), the increase in M_n^{R} , the increase in M_n^{L} and the decrease in M_t^{Th}. Also note the increase in total clockwise moment produced by virtual finger, approximately compensating for the decreased clockwise moment due to normal force of the thumb. The columns and error bars indicate means and standard error of means.

The decrease in the clockwise moment of thumb tangential force M_t^{Th} was counteracted by the increase in the total clockwise moment (decrease in the counter-clockwise direction) due to the virtual finger M_{tot}^{VF} (see Supplementary Figure S1). Increase in the moment due to normal force of virtual finger in free condition was mainly due to the increase in the normal force of middle, ring and little finger, not index finger.

We performed pairwise post-hoc tukey tests on M_n^{VF}, M_n^{R} and M_n^{L} which showed significant increase ($p<0.001$) in clockwise direction in free condition (-92.25 (VF), -40.89 (R), -103.15 (L)) Nmm compared to fixed condition (-4.79 (VF), -17.20 (R), -39.50 (L)) Nmm. Pairwise post-hoc comparisons showed a significant decrease ($p<0.001$) in the clockwise direction of M_t^{Th} in free condition (-36.09 Nmm) compared to fixed condition (-89.24 Nmm).

Statistically significant decrease in counter-clockwise direction was found in M_{tot}^{VF} in free condition (48 Nmm) compared to the fixed condition (95.01 Nmm).

In fixed condition, the moment due to the normal force of VF was 4Nmm in the clockwise direction, but the same was much higher in the free condition. The increase in the clockwise moment due to normal force of VF (92Nmm) in the free condition was mainly due to the greater increase in the normal force of ring & little finger and a moderate increase in the normal force of the middle finger. In free condition, due to the thumb mobility, the moment due to thumb tangential force dropped across all participants as there was insufficient friction due to the slider mechanism found between the thumb sensor platform and the handle. This result is in agreement with the study of Aoki and colleagues (2006) where the participants exhibited a greater drop in the tangential force at the low friction contacts.

Supplementary Note on the Synergy analysis

Finger force covariation was quantified to examine the existence of synergy. For the purpose of this manuscript, we use a previous definition of "synergy" as "a neural organization of a set of elemental variables with a purpose of stabilizing a certain performance variable"(Latash, 2008).

As in the previous studies (Latash, 2008; SKM et al., 2012; Zhang et al., 2009; Sun, Zatsiorsky & Latash, 2011; Latash, Scholz & Schöner, 2002), synergy analysis on the mechanical variables was performed at two different levels: Virtual Finger-Thumb (VFTH) level and the Virtual finger (VF) level (see supplementary Note on Synergy analysis)

Index of synergy or index of covariation (ΔV) was computed to quantify the amount of covariation that occurs within the elemental variables. Positive values of ΔV indicates negative covariation among the elemental variables. This, in turn, means the existence of synergy for that particular variable during the task. This index was computed across 30 trials for each participant separately, and then the average of ΔV (across time) was computed for each participant. This data was averaged across 15 participants, and SEM was found.

Synergy index was calculated by using the below equation.

$$\Delta V = \frac{\sum Var(EVs) - Var(PV)}{\sum Var(EVs)} \qquad \text{(Supplementary Equation S7)}$$

EV refers to the elemental variables and PV refers to performance variables. Index of covariation (ΔV) was computed across 30 trials for each participant separately and then across time average of ΔV was performed for each participant. This data was averaged across 15 participants and standard error of mean was found. Fisher Z transformation was performed to the ΔV values of each participant for statistical analysis by using the following equation.

$$\Delta V_z = 0.5 * ln\left(\frac{1+\Delta V}{1-\Delta V}\right) \qquad \text{(Supplementary Equation S8)}$$

Synergy index was calculated for the following performance variables found on the left-hand side of the below equations (Zhang et al., 2009).

At VFTH level:

$$F_n^{VFTH} = F_n^{VF} + F_n^{Th} \quad \text{(Supplementary Equation S9)}$$

$$F_t^{VFTH} = F_t^{VF} + F_t^{Th} \quad \text{(Supplementary Equation S10)}$$

$$M_{tot}^{VFTH} = M_n^{VF} + M_t^{Th} + M_t^{VF} + M_n^{Th} \quad \text{(Supplementary Equation S11)}$$

At VF level:

$$F_n^{VF} = F_n^{I} + F_n^{M} + F_n^{R} + F_n^{L} \quad \text{(Supplementary Equation S12)}$$

$$F_t^{VF} = F_t^{I} + F_t^{M} + F_t^{R} + F_t^{L} \quad \text{(Supplementary Equation S13)}$$

$$M_n^{VF} = M_n^{I} + M_n^{M} + M_n^{R} + M_n^{L} \quad \text{(Supplementary Equation S14)}$$

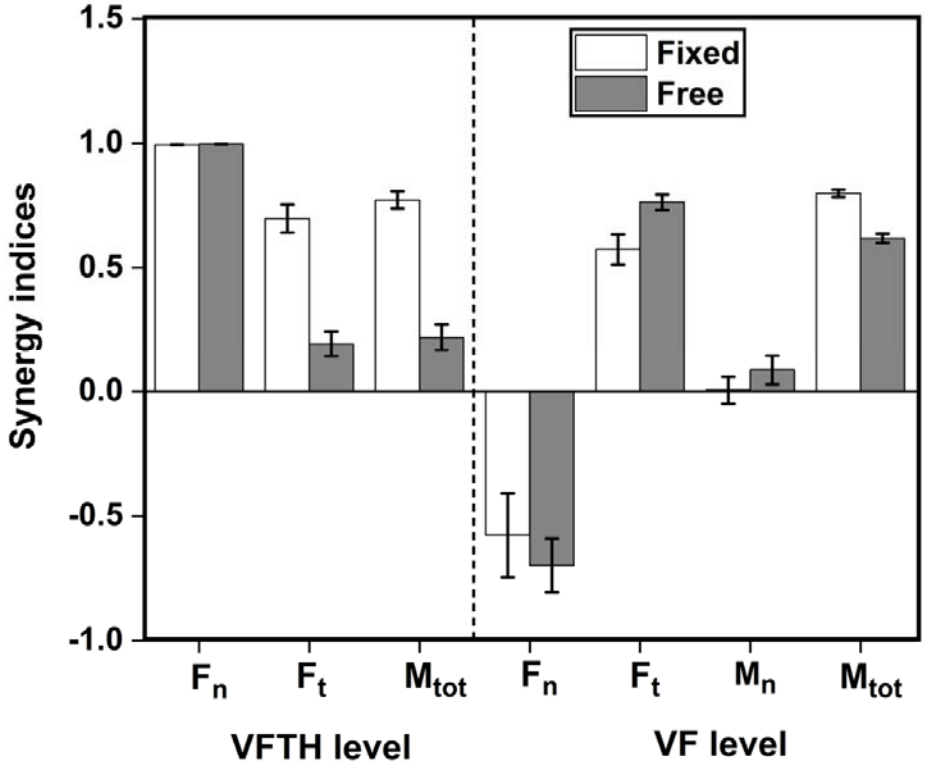
$$M_{tot}^{VF} = M_n^{VF} + M_t^{VF} \quad \text{(Supplementary Equation S15)}$$

n and t stands for normal and tangential forces. I,M,R,L, Th and VF refers to Index, Middle, Ring, Little, Thumb and Virtual finger.

One-way repeated measures ANOVA were performed on the z-transformed synergy indices at VFTH & VF level with the condition as a factor.

For all the three performance variables at VFTH level, ΔV indices were positive during the fixed and free conditions (see Supplementary Figure S2). Note that the ΔV indices at VF level were positive for tangential force and total moment (M_{tot}) in both conditions. Supplementary Figure S2 presents actual ΔV values, whereas statistical analysis was performed with Z-transformed ΔV values.

The observations about the synergy indices for the Z-transformed performance variables (ΔV_z) at VFTH and VF levels were tested by using one-way repeated measures ANOVAs with conditions as a factor. It was found that there was a significant difference ($F_{(1,14)}$=8.9013;$p<0.05$, η^2_p =0.38) between fixed and free condition on ΔV_z of the normal force at VFTH level. Also there was a significant decrease in ΔV_z of the tangential force ($F_{(1,14)}$=58.88; $p<0.001$, η^2_p =0.80) and ΔV_z of the total moment ($F_{(1,14)}$=60.50; $p<0.001$, η^2_p =0.81) in free condition (0.20, 0.23) when compared with the fixed condition (0.99, 1.09) at VFTH level. A significant increase ($F_{(1,14)}$=8.23; $p<0.05$, η^2_p =0.37) was seen in the ΔV_z of the tangential force (VF level) in free condition (1.08) in comparison to the same in fixed condition (0.71). ΔV_z of the total moment (VF level) showed a significant decrease ($F_{(1,14)}$=57.99; $p<0.001$, η^2_p =0.80) in free condition (0.73) compared to fixed condition (1.11).`



Supplementary Figure S2. Synergy indices(ΔV) for different performance variables at VFTH and VF level Synergy index for the performance variables at VFTH level: Normal force(Fn),Tangential force(Ft) and Total moment(Mtot) are shown on left side of the vertical dashed line. Synergy index for the performance variables at VF level: Normal force(Fn), Tangential force(Ft), Moment due to normal force(Mn) and Total moment(Mtot) are shown on right side of the vertical dash line. Synergy indices for Tangential force at VFTH level significantly decreased ($p<0.001$) in free condition compared to fixed condition Synergy indices for tangential force at VF level significantly increased ($p<0.01$) in free condition compared to fixed condition. Synergy indices for Mtot (VFTH and VF level) significantly decreased ($p<0.001$) in free condition compared to fixed condition. The columns and errorbars indicate means and standard error of means.

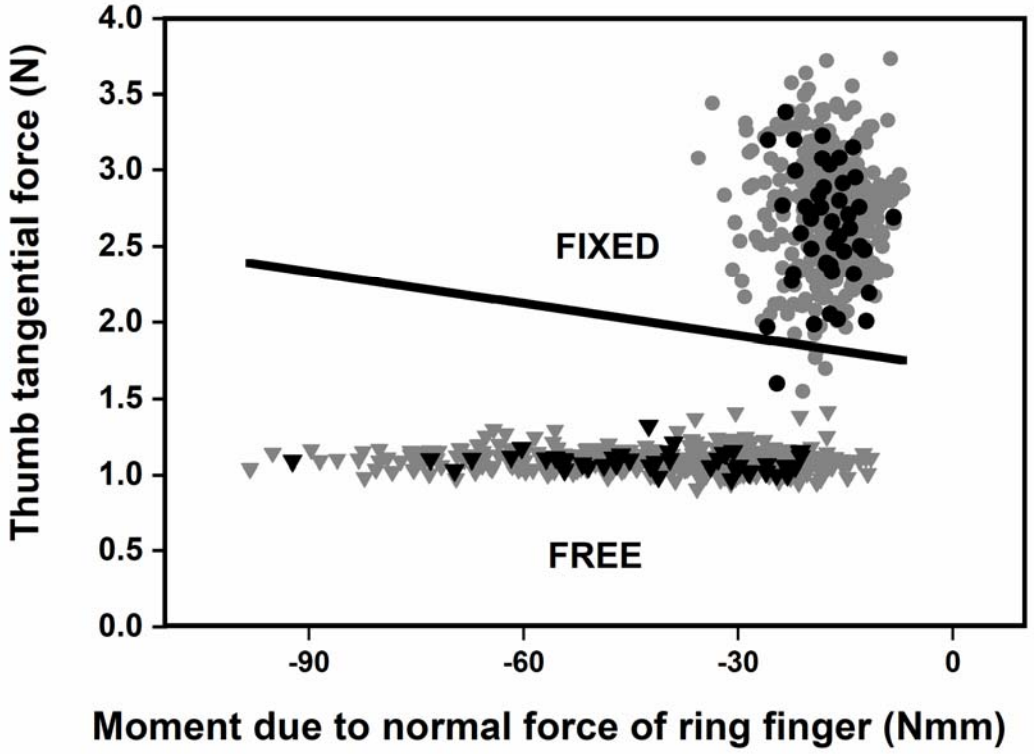
Prehension synergies have been explained within the framework of the Uncontrolled Manifold (UCM) hypothesis (Scholz & Schöner, 1999). Control of the hand and finger action has been viewed as a two-level hierarchical organization(MacKenzie & Iberall, 1994). The elemental variables at a higher level are forces and the moments produced by thumb and VF (VFTH level). At the lower level (VF Level), elemental variables are forces and moments generated by index, middle, ring, and little fingers. The sign and magnitude of synergy indices help to quantify the neural organization of the elemental variables involved in the task(Gelfand & Latash, 1998), as it is interpreted to be a direct measure of the CNS activity

in response to any change in the task characteristics. Though this kind of co-variation analysis is different from the classical UCM analysis(Latash, Scholz & Schöner, 2002), the outcome measures in both approaches signify similar behaviour.

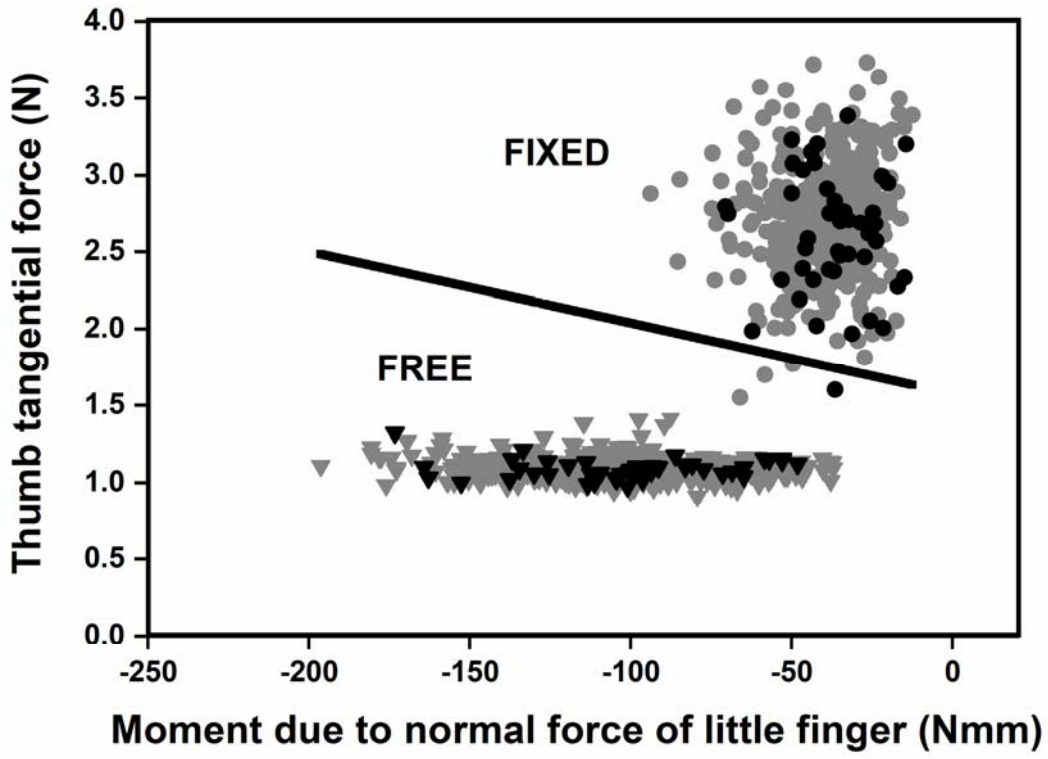
Positive index of covariation was observed for the performance variables like normal force, tangential force, and the total moment at VFTH level both during the fixed and free conditions (see Supplementary Figure S2). Large positive ΔV values (closer to +1) were found for the normal force at the VFTH level in both conditions suggesting the prevalence of a strong synergy. To achieve grasp stability, fingertip forces and moments (Mn and Mt) of VF and thumb adjust systematically among them, confirming the presence of synergy. In free condition, synergy indices for the tangential force and total moment in VFTH level decreased. This destabilization of tangential force and total moment in VFTH level could complicate the maintenance of rotational equilibrium during the free condition (when the thumb could move in the vertical direction). The drop in the ΔV value for the tangential force, the performance variable, signifies the reduction in synergic action when the handle equilibrium is disturbed. Meanwhile, for the other performance variable at the VFTH level, the normal force, ΔV value remains approximately the same. Thus, despite a decrease in the coordination of tangential force and total moment, the horizontal equilibrium is not compromised. At VF level, synergy index for tangential force increased in the free condition which means the facilitation of stronger synergies by the system. Negative index of co-variation was seen in the normal force in fixed as well as free condition. There was no synergy for the moment due to normal force at the VF level.

From Supplementary Figure S2, we observe that the synergy indices of performance variables like tangential force and total moment were different in free condition compared to the fixed condition. This reflects the fact that a synergic solution is preferred when the task characteristic is altered. There was a deterioration in the synergy indices of tangential force (a drop of 72%) at the VFTH (higher) level in free condition. However, there was a substantial increase of 33% in the synergy indices of tangential force at the VF (lower) level. This implies that the elemental variables involved in stabilizing tangential force at the lower level (i.e., tangential forces of index, middle, ring and little finger) co-adjust among themselves actively, thereby ensuring proper coordination within the individual fingers other than the thumb. An increase in the tangential force coordination at the lower level of the hierarchy compensated for the poorer tangential force coordination at a higher level. In free condition, synergy indices of the total moment at higher level dropped to about 71%, whereas at a lower level the drop was only 22%. Though there was a drop in both levels, the drops are not comparable. Such an inherent trade-off between synergies at two levels of a hypothetical hierarchy observed in our study are in broad agreement with previous studies on multi-digit synergies in similar prehension task (Gorniak, Zatsiorsky & Latash, 2007, 2009; Latash, 2008). We believe that the CNS preferred to change the strength of synergy for multiple performance variables (further with changes in multiple elemental variables at multiple levels of hierarchy) to achieve stability in task performance.

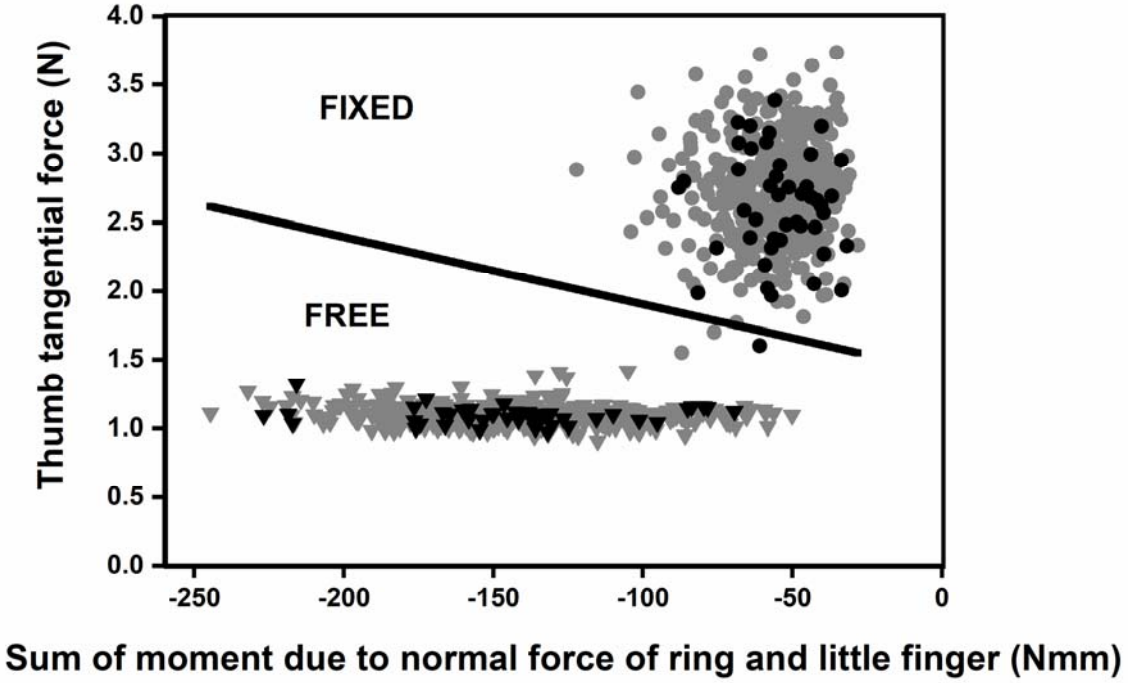
Supplementary Figures on the Linear discriminant analysis



Supplementary Figure S3. Thumb load force (LF-TH) as a function of Moment due to the normal force of ring finger (Mn-R). Each datapoint in the scatter plot represents time average of a single trial of a single subject. Data from all subjects are presented. Inverted triangle in grey & black colours are train (405) and test (45) datapoints in free condition. Circles in grey & black colours are train (405) and test (45) datapoints in fixed condition. Note: Only one test datapoint belonging to fixed condition was wrongly classified as free condition, so the accuracy of classification is 98%, sensitivity is 100%, specificity and precision is 97%, false positive rate is 2% in all the four cases.



Supplementary Figure S4. Thumb load force (LF-TH) as a function of Moment due to the normal force of little finger (Mn-L). Each datapoint in the scatter plot represents time average of a single trial of a single subject. Data from all subjects are presented. Inverted triangle in grey & black colours are train (405) and test (45) datapoints in free condition. Circles in grey & black colours are train (405) and test (45) datapoints in fixed condition. Note: Only one test datapoint belonging to fixed condition was wrongly classified as free condition, so the accuracy of classification is 98%, sensitivity is 100%, specificity and precision is 97%, false positive rate is 2% in all the four cases.



Supplementary Figure S5. Thumb load force (LF-TH) as a function of sum of the Moment due to normal force of ring and little finger (Mn-RL). Each datapoint in the scatter plot represents time average of a single trial of a single subject. Data from all subjects are presented. Inverted triangle in grey & black colours are train (405) and test (45) datapoints in free condition. Circles in grey & black colours are train (405) and test (45) datapoints in fixed condition. Note: Only one test datapoint belonging to fixed condition was wrongly classified as free condition, so the accuracy of classification is 98%, sensitivity is 100%, specificity and precision is 97%, false positive rate is 2% in all the four cases.

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