Evidence to support the mechanical advantage hypothesis of grasping at low force levels

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Abstract

Grasping an object is one of the several tasks performed by human hands. Object stabilization while grasping is a fundamental aspect to consider for the safety of grasped objects. Fingertip forces re-distribute to establish equilibrium when systematic variations are introduced to objects held in hand. During torque variations to the grasped handle, the central nervous system prefers to support the mechanical advantage hypothesis. According to this hypothesis, during torque production tasks, fingers with longer moment arm for normal force produce greater normal force than the fingers with shorter moment arm. The current study was performed to examine and confirm the factor that causes the central nervous system to employ this strategy. In addition to minimising the thumb's contribution to hold the handle, thumb normal force was restricted to a minimal level. Such a restriction made the task even more challenging. Therefore, it was confirmed that the challenging task induces the central nervous system to employ the mechanical advantage principle.

Introduction

Human hands play a vital role in accomplishing a multitude of daily life activities, from object manipulation to exploration. Grasping is one common activity performed with the human hands of all healthy individuals. Object stabilization while grasping is the foremost important aspect to be considered for safe manipulation. Fingertip forces of the individual fingers finely adjust to maintain the handle in static equilibrium to achieve object stabilization.

The force distribution of the individual fingers was studied when the mass[1], torque[2], fingertip position[3], and surface friction[4,5] of the object were varied systematically. During any torque changes to the handheld object, our central nervous system prefers to make use of the mechanical advantage of the fingers to minimize the total effort (or force)[6]. According to the mechanical advantage hypothesis (MAH), peripheral fingers with longer moment arms for the normal force during the moment production tasks produce greater normal force than the central fingers with shorter moment arms for normal force. In the past, there were studies performed with five fingers prehensile handles to investigate the applicability of the mechanical advantage hypothesis.

In a study on the prehensile handle, load and torque changes were introduced to the handle by suspending loads of different masses at various distances from the handle's center of mass (COM)[7]. The instruction was to maintain the handle in static equilibrium. Due to the external torque changes, either index or little finger produced greater normal force than middle or ring finger depending on the torque direction. Thus, supporting the mechanical advantage hypothesis. Further, MAH was also supported in the study that involved an accurate handle rotation task involving five digits of the human hand[8,9]. In a multi-finger torque production study[6], the use of mechanical advantage was investigated on a mechanically fixed and free handle. The results of the study supported the idea that the central nervous system utilizes the mechanical advantage during torque production in both fixed and free objects.

Further, our preliminary study on the five-fingers prehensile handle examined the mechanical advantage hypothesis when torque changes were introduced by placing the thumb on a slider platform mounted over a vertical railing fitted on the handle frame[10]. Due to the unsteady thumb platform, the tangential force contribution of the thumb was constant and low, thus resulting in the pronation torque. As the instruction was to maintain the handle in static equilibrium, a compensatory supination torque was required. Thus, in the absence of mechanical constraint to fix the platform, the normal force of the ulnar fingers increased to produce the compensatory supination torque. The expectation was that, during the compensatory torque production, the little finger would exert greater normal force than the ring finger. In contrast to our expectation, ulnar fingers exerted statistically comparable normal forces when the unsteady thumb platform was held steady at the HOME position (midway between middle and ring fingers)

The mechanical advantage hypothesis was partially supported by a study involving moment production on a mechanically fixed vertically oriented handle[11]. It was assumed that the applicability of MAH is limited and specific to task and effector. Since there was no supportive evidence to explain this, we attempted to examine whether the applicability of the mechanical advantage principle is specific to any particular task and investigate the kind of task that lends support to MAH. To investigate this, our previous study involved systematically increasing the mass of the handle by adding external loads of mass 0.150kg, 0.250kg, 0.350kg, and 0.450kg[12]. With the addition of external loads, the magnitude of supination torque requirement also increased. The expectation was that MAH would be supported with the addition of external load. However, MAH was supported only when an external load of a greater mass of 0.450kg was added. Since the thumb contribution to hold the handle was restricted to constant low magnitude, the other fingers were required to share the increasing load. Therefore, we believed that the abstract sense of challenge experienced to maintain the handle in equilibrium with a larger external load of mass 0.450kg, could be the reason for MAH to be supported.

There are different ways by which a task can be made challenging or difficult. It can be done by increasing the mass, reducing the surface friction of the grasped object, suspending a larger external load at a greater distance from the center of mass of the handle, and operating the fingers or thumb beyond their restricted range of motion. These situations demand greater normal force to be produced by the fingers and thumb for the successful completion of the task. Also, it is possible to make the task more difficult by imposing restrictions on the normal force produced by the thumb. As it is, when the thumb is placed on a movable slider platform, it is difficult to maintain the handle in static equilibrium. Further, when the normal force of the thumb is restricted to a low level, the task becomes even more challenging. In the current study, there are three constraints on the thumb: low normal force, low tangential force, minimal or no movement of a movable platform. Therefore, the task of maintaining the static equilibrium of the handle was quite difficult to perform. In such a situation, the expectation was that CNS might prefer to use the little finger's mechanical advantage by producing greater normal force than the ring finger to complete the task successfully.

Thus, we hypothesized that CNS utilizes the mechanical advantage when the task is made demanding by instructing them to produce minimal thumb normal force (uncomfortable grasp) while holding the handle with an unsteady platform (Hypothesis 1).

Methods And Materials

Participants

Twelve right-handed male participants participated in this experiment. The mean and the standard deviation of height, weight, hand length, and width of the participants were Age: 26.66±3.22years, Height: 171.33±7.54 cm, Weight: 76±13.17kg, Hand-length: 19.31±0.70cm, and Hand-width: 9.02±0.42cm. Participants with no history of musculoskeletal injuries and neurological diseases were chosen to participate.

Ethics Approval

The experimental procedures were approved by the Institutional Ethics committee of the Indian Institute of Technology Madras (Approval Number: **IEC/2021-01/SKM/02/05).** All the participants gave written informed consent according to the procedure approved by the institutional ethics committee of IIT Madras before starting the experiment. The experiment was conducted by strictly adhering to the procedures approved by the Institutional Ethics Committee of the Indian Institute of Technology Madras.

Experimental setup

A five-finger instrumented prehensile handle was designed and built with a vertical railing of length 13.6cm on the thumb side of the handle frame (see Fig. 1). A slider platform was mounted on the railing to translate in the vertical direction over the railing. The mass of the slider platform was 0.100kg. The handle with slider platform was suspended from the top of wooden support using a nylon rope housed within a PVC pipe to prevent unnecessary lateral movements. The total mass of the handle, including the slider platform, was 0.450kg. Five six-axis force/torque sensors (Nano 17, Force resolution: Tangential: 0.0125N, Normal: 0.0125N, ATI Industrial Automation, NC, USA) were mounted on the handle to measure the forces and moments exerted by the individual fingers and thumb. The force sensor for the thumb alone was placed on the slider platform.

An acrylic block was placed in the anterior-posterior direction on top of the handle. An intelligent 9-axis absolute orientation sensor (Resolution: 16bits, Range: 2000º/s, Model: BNO055, BOSCH, Germany) was placed on the acrylic block towards the monitor side. This IMU (Inertial Measurement Unit) measured the position and orientation of the handle during the experiment. Further, on top of the handle, towards the thumb side, a square acrylic piece was fitted to mount a laser displacement sensor (resolution, 5μm; OADM 12U6460, Baumer, India). This displacement sensor was mounted to measure the displacement data of the thumb platform in the vertical direction while it translated along the vertical railing. A spirit level with a bull’s eye was placed on the acrylic block towards the participant’s side to check whether the handle was vertically oriented.

Two horizontal lines were drawn on the participant’s side of the handle, one at the center of the thumb platform and another line drawn midway between the middle and ring fingers (represents ‘HOME’ position) on the handle frame. The participants were instructed to place the unsteady thumb platform by precisely aligning both lines while holding the handle. 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 four channels of processed, digital data from the IMU sensor.

Experimental procedure

Participants were asked to wash their hands with soap and towel dry before the start of the experiment. The right upper arm was abducted approximately 45° in the frontal plane, flexed 45° in the sagittal plane with the elbow flexed at approximately 90°. The natural grasping position can be achieved by supinating the forearm at 90°. The movements of the forearm and wrist were constrained by fastening with a velcro strap to the tabletop.

The experiment consisted of two conditions: comfortable grasp and uncomfortable grasp. During both the conditions, the task was to maintain the handle in static equilibrium by holding the slider platform steady at the HOME position. Apart from this, in comfortable grasp condition, the target thumb's normal force was set to 14N. The participant’s computer monitor displayed only the solid horizontal target line corresponding to the target thumb normal force with two dashed lines, one above and below the solid line representing an error margin of ±0.5N (see Fig. 2). The participants were instructed to hold the platform steady by producing a thumb normal force which was shown as a visual feedback line to trace the solid horizontal target line. The trial was accepted only when the thumb’s normal force’s feedback line was within the acceptable error margin. Thus, the task of producing thumb normal force of 14N matching the target normal force line had to be performed by precisely aligning the horizontal line on the thumb platform to the line drawn on the handle frame.

In uncomfortable grasp condition, the target thumb normal force was set to 7N. The participants were instructed to produce a minimal thumb normal force of 7N, which would be fed as a feedback line to trace the target line corresponding to 7N. This tracing task had to be performed by aligning the horizontal line on the thumb platform to the line drawn on the handle frame. The acceptable error margin of thumb displacement data for both conditions was ±0.2cm. Throughout the trial, in both conditions, the participants were instructed to avoid tilting the handle in any direction by maintaining the bubble at the center of the spirit level. The experimenter could view the thumb displacement data, net tilt angle, normal and tangential forces of the individual fingers and thumb on a separate computer monitor (not viewable by the participant).

For each experimental condition, twenty-five trials were provided. Each trial lasted ten seconds. One minute break was provided between the trials. One hour break was provided between the conditions. Six participants performed comfortable grasping in their first session, and the remaining six participants performed uncomfortable grasping in their first session. In this way, the order of conditions was counterbalanced across participants.

Data analysis

In each trial, the data between 3s and 7s were taken for analysis to avoid start and end effects. The collected data were analyzed offline using MATLAB (Version R2016b, MathWorks, USA). Force/Torque data and laser displacement data of thumb were lowpass filtered at 15Hz using second-order, zero phase lag Butterworth filter. The normal and tangential force data collected from the individual fingertips and the thumb were averaged over the time samples, trials, and participants for each condition separately, and the standard errors of the mean were computed.

Statistics

All statistical analyses were performed using R. We performed a two-way repeated-measures ANOVA on the average normal force with the factors as *conditions* (2 levels: comfortable grasp and uncomfortable grasp) and *fingers* (4 levels: index, middle, ring, little). Since the thumb's normal force was dependent on the normal forces produced by index, middle, ring, and little fingers, the thumb was excluded from the ANOVA analysis. Sphericity test was done on the data, and the number of degrees of freedom was adjusted by Huynh-Feldt (H-F) criterion wherever required. We also performed pairwise post hoc tukey tests to examine the significance within factors. An equivalence test was performed on the normal forces of the ulnar fingers collected during comfortable grasp condition. The statistical equivalence was tested using the two one-sided t-tests (TOST) approach[13] for a desired statistical power of 95%. The smallest effect size of interest (SESOI) was chosen as the equivalence bounds.

Results

Task performance

All the participants could trace the target normal force line during both conditions by producing appropriate thumb normal force within the error margin of ± 0.5N. The root mean square error of the thumb normal force data was computed for comfortable and uncomfortable grasp conditions, shown in Table 1. Also, all the participants were able to produce the target force by aligning the horizontal line on the platform to the line drawn between middle and ring fingers within an acceptable error margin of ± 0.2cm. The root mean square error of the thumb displacement data was also calculated and shown in Table 1.

Table 1
Root mean square error of the thumb data and net tilt angle during comfortable and uncomfortable grasp conditions. The table shows the average net tilt angle of the handle and root mean square error on the thumb normal force and displacement data during both grasp conditions. The mean and standard deviation (SD) of the data are presented.

Condition	**RMSE of the thumb normal force data (N)** **(mean ± SD)**	**RMSE of the thumb displacement data (cm)** **(mean ± SD)**	**Net tilt angle (degrees)** **(mean ± SD)**
Comfortable grasp	0.24 ± 0.05	0.09 ± 0.02	0.72 ± 0.24
Uncomfortable grasp	0.36 ± 0.07	0.11 ± 0.01	0.78 ± 0.25

Normal forces of the individual fingers during comfortable and uncomfortable grasp

During comfortable grasp condition, the normal forces of the ring (Mean = 4.61N, SD = 0.70) and little (Mean = 4.49N, SD = 0.57) fingers were found to be statistically comparable ($t(11) = -3.207$, $p = 0.00418$). This was confirmed by employing the TOST procedure with equivalence bounds of $\Delta_L = -1.04$ and $\Delta_U = 1.04$ for a desired statistical power of 95%. However, during uncomfortable grasp condition, the normal force produced by the little finger (Mean = 3.36N, SD = 0.41) was statistically ($p < 0.001$) greater than the normal force produced by the ring finger (Mean = 2.13N, SD = 0.43) and thus supporting the mechanical advantage hypothesis (refer Fig. 3).

We performed a two-way repeated-measures ANOVA on the average normal force with the factors *condition* and *fingers* that showed the main effect of condition ($F_{(1, 11)} = 15{,}106.26$; $p < 0.001$, $\eta^2_p = 0.99$) corresponding to a statistically greater normal force for comfortable grasp compared to uncomfortable grasp. Similarly, the main effect of the factor *fingers* ($F_{(2.85, 31.35)} = 81.264$; $p < 0.001$, $\eta^2_p = 0.88$) exhibited a statistically ($p < 0.001$) greater normal force by the ulnar fingers compared to the radial fingers.

The interaction *condition x fingers* ($F_{(3.12, 34.32)} = 15.23$; $p < 0.001$, $\eta^2_p = 0.58$) showed a statistical effect reflecting the fact that the ulnar finger normal forces (Ring: Mean = 4.61N, SD = 0.70; Little: Mean = 4.49N, SD = 0.57) during comfortable grasp was statistically greater ($p < 0.001$) than during uncomfortable grasp (Ring: Mean = 2.13N, SD = 0.43; Little: Mean = 3.36N, SD = 0.41).

The post hoc pairwise tukey test confirmed that the ring (Mean = 4.61N, SD = 0.70) and little finger (Mean = 4.49N, SD = 0.57) normal force of comfortable grasp condition was found to be statistically greater ($p < 0.001$) than the radial finger normal forces of both simple (Index: Mean = 1.88N, SD = 0.33; Middle: Mean = 2.76N, SD = 0.64) and uncomfortable grasp (Index: Mean = 0.65N, SD = 0.16; Middle: Mean = 1.01N, SD = 0.28) condition.

The task of maintaining the static equilibrium of the handle by producing a minimal normal force by the thumb along with the restriction to align the horizontal lines on the handle makes the task quite challenging.

Index finger normal force (Mean = 1.88N, SD = 0.33) of comfortable grasp was found to be statistically lesser ($p < 0.001$) than the middle finger normal force (Mean = 2.76N, SD = 0.64) of the same condition and little finger normal force of uncomfortable grasp (Mean = 3.36N, SD = 0.41). Meanwhile, the middle finger normal force of comfortable grasp condition (Mean = 2.76N, SD = 0.64) was statistically greater ($p < 0.001$) than index (Mean = 0.65N, SD = 0.16), middle (Mean = 1.01N, SD = 0.28) and ring fingers (Mean = 2.13N, SD = 0.43, $p < 0.05$) of uncomfortable grasp condition. In addition to this, during uncomfortable grasp, the ulnar fingers normal forces (Ring: Mean = 2.13N, SD = 0.43; Little: Mean = 3.36N, SD = 0.41) was statistically greater ($p < 0.001$) than radial finger (Index: Mean = 0.65N, SD = 0.16; Middle: Mean = 1.01N, SD = 0.28) normal forces.

Discussion

The main objective of the current study was to check and confirm whether the support for the mechanical advantage principle depends on the challenge associated with the task. The little finger produced a greater normal force than the ring finger when the thumb was restricted to produce a normal force of 7N closer to the mass of the handle. We believed that the reason could be due to the challenge of maintaining the handle equilibrium by producing lesser normal force by the thumb. In addition to the restriction on the normal force of the thumb, there was restriction imposed on its position and tangential force. The cause and effect behind the results will be discussed in the following paragraphs.

Some of the studies in the past supported the mechanical advantage principle in certain conditions. In a five-finger prehension study, when a load of greater mass (2kg) was suspended closer (1.9cm) to COM of the handle, ulnar fingers exerted apparently comparable normal force[7]. However, when the same external load was suspended at a farther distance (7.6cm) from COM, causing a greater moment, the little finger produced greater normal force than the ring finger. Similarly, in another multi-finger prehension study, MAH was supported even when a load of lesser mass (less than 2kg) was suspended at a greater distance (8.9cm) from COM of the handle[14]. Thus, this does not mean that the support for MAH is always dependent on the moment arm or mass of the suspended load or magnitude of moment requirement.

Our previous study on the systematic increase in the mass of the handle with the load suspended exactly below COM of the handle could help to understand this situation better[12]. Although external loads of mass ranging from 0.150kg to 0.450kg were suspended exactly below COM of the handle, MA principle was supportive only when an external load of mass 0.450kg was added. From the results, it may be posited that the support for mechanical advantage principle could be due to an abstract sense of challenge associated either with the mass of the suspended load, moment arm or magnitude of moment requirement.

Apart from this, the hypothesis was also supported when the thumb platform was made to operate in the region beyond the range of motion of carpometacarpal (CMC) joint of thumb during the pattern tracing study[15]. The study was comprised of two conditions: tracing trapezoid pattern and inverted trapezoid pattern. Depending on the condition, either trapezoid or inverted trapezoid pattern was displayed on the computer monitor. The task was to hold the handle with the unsteady thumb platform at the HOME position for a few seconds and translate the platform vertically towards the index finger side (during trapezoid condition) or little finger side (during inverted trapezoid condition). CMC joint of the thumb possesses a limited range of motion in the downward direction. Therefore, tracing the BOTTOM static portion of the inverted trapezoid pattern was quite challenging than tracing the TOP static portion of the trapezoid pattern. Although a greater compensatory moment was required due to the shift in the position of the thumb platform from HOME, the challenge associated with operating the thumb beyond the range of motion of its CMC joint could also be the reason for supporting MAH.

In the current study, maintaining the handle in static equilibrium was challenging by imposing restrictions on the thumb's normal force. The magnitude of target normal force to be produced by the thumb during comfortable grasp condition, was chosen from the results of our previous study on the systematic increase in the mass of the handle. As per the previous study, when there was no restriction on the normal forces, the average normal force produced by the thumb was approximately 14N when the total mass of the handle was 0.700kg. The results showed a statistically comparable normal forces by the ulnar fingers. Therefore, for the current study, we expected that the ulnar fingers would continue to produce a statistically comparable normal force during comfortable grasping. Whereas, in the case of uncomfortable grasp condition, the target normal force was set to 7N. Since the total mass of the handle with the external load was 0.700kg, the total tangential force shared by the fingers and thumb for holding the handle, including the cable mass, was approximately 6.86N. Therefore, for uncomfortable grasp condition, the instruction was to exert a thumb normal force of 7N.

In addition to the restriction on the thumb normal force, a constraint was already imposed on the handle design. That is, there are two different interfaces on the thumb side of the handle: the thumb-platform interface and platform-railing interface. Since the slider platform was mounted on the vertical railing fitted over the handle frame, the friction at the platform-railing interface was very low ($\mu \sim 0.001$ to 0.002). Therefore, the tangential force produced by the thumb to hold the platform was maintained at a constant low magnitude. Additionally, throughout the entire trial, the slider platform had to be held at the HOME position by aligning the horizontal lines on the platform and the handle frame. In the presence of all these three constraints, maintaining the static equilibrium of the handle was quite challenging to perform.

During comfortable grasp condition, the task of maintaining the static equilibrium of the handle was not challenging enough as the target thumb normal force was almost double that of the mass of the handle. Therefore, as seen in our preliminary study[10], the ring and little fingers shared statistically comparable normal forces to balance the horizontal equilibrium (see Introduction section). However, during uncomfortable grasp condition, the little finger produced greater normal force than the ring finger, supporting the mechanical advantage hypothesis. Since the target thumb normal force during uncomfortable grasp condition was 7N lesser than the target normal force set for comfortable grasp condition, the ulnar finger normal forces decreased. The decrease in the ulnar finger normal forces would be accompanied by a drop in the supination torque, as ulnar finger normal forces are contributors to supination torque. In response to this, there would be a pronation torque in the anti-clockwise direction due to the virtual finger tangential force. However, to maintain the rotational equilibrium of the handle, a sufficient compensatory supination torque was required without a substantial increase in the ulnar finger normal forces. Perhaps, by increasing both ring and little finger normal forces together, virtual finger normal force might increase, which might indirectly disturb the normal force produced by the thumb.

Therefore, during uncomfortable grasp condition, the aim was to produce a sufficient supination torque without showing a greater increase in the total normal force of the ulnar fingers. Employing the mechanical advantage principle would be the best solution from the mechanics perspective. It involved increasing the normal force of the little finger than the ring finger. Thus, sufficient supination torque was produced while simultaneously producing minimal total normal force. It is inferred that when multiple constraints are imposed simultaneously, MAH is supported.

It is possible to untangle the intricate details behind the results of both the conditions from an anatomical or biomechanical standpoint. The tendons of the extrinsic muscle, flexor digitorum profundus (FDP), extend to the distal interphalangeal (DIP) joints of the index, middle, ring, and little fingers. FDP muscle is responsible for the flexion of DIP joints of the four fingers and thus accountable for the normal force production in those fingers. Whereas the intrinsic muscles of the hand such as lumbricals, hypothenar, thenar, dorsal and palmar interossei muscles are involved in the precise (or dexterous) manipulation of the object[16–18].

In the case of comfortable grasp condition, since the thumb exerted a relatively high normal force of 14 N, extrinsic muscles responsible for forceful grip production would attempt to increase the virtual finger normal force. In particular, the forces of ulnar fingers increase more than the radial fingers (index and middle) due to the task requirement of compensatory supination torque. In the case of uncomfortable grasp condition, since maintaining the handle equilibrium was quite challenging, dexterous control of ulnar finger normal forces was required for the minimal total normal force production and sufficient compensatory torque production. Among the ulnar fingers, the little finger has an additional group of intrinsic muscles referred to as hypothenar muscles (flexor digiti minimi, abductor digit minimi, opponens digiti minimi) in addition to the lumbrical muscle.

Since the little finger has the added advantage of a separate group of intrinsic muscles for the dexterous manipulation compared to the ring finger, CNS might have attempted to use the little finger compared to the ring finger as it has both anatomical and mechanical advantages. Hence, the little finger might have produced a greater normal force than the ring finger, supporting the mechanical advantage hypothesis. The unique muscle architecture of the little finger may be why the system chooses to employ the mechanical advantage principle, particularly when the task becomes challenging, as in the current study.

Concluding Comments

Maintaining the static equilibrium of the handle by producing the thumb's normal force closer to the mass of the handle, which already has restrictions imposed on the thumb's tangential force and position, makes the task quite challenging. Since the little finger has both anatomical and mechanical advantages, CNS might have decided to use the little finger to complete the task successfully. Thus, the challenge associated with the task had induced CNS to use the little finger, supporting the mechanical advantage hypothesis, by producing greater normal force in the little finger than the ring finger.

Declarations

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Author Contributions Statement

Conceptualization – BR, VSKM; Methodology – BR, VSKM; Formal Analysis – BR; Writing Original Draft – BR; Writing, Review, and Editing –BR, VSKM.

Competing interests

The authors declare no competing interests.

Data Availability

We plan to publish a data descriptor article along with this manuscript. Hence the data will be made available in due course of time.

References

1. Johansson, R. S. & Westling, G. Coordinated isometric muscle commands adequately and erroneously programmed for the weight during lifting task with precision grip. *Exp Brain Res* **71**, 59–71 (1988).
2. Zatsiorsky, V. M., Gao, F. & Latash, M. L. Prehension synergies: Effects of object geometry and prescribed torques. *Exp Brain Res* **148**, 77–87 (2003).

3. Solnik, S., Zatsiorsky, V. M. & Latash, M. L. Internal Forces during Static Prehension: Effects of Age and Grasp Configuration. *J Mot Behav* **46**, 211–222 (2014).
4. Aoki, T., Latash, M. L. & Zatsiorsky, V. M. Adjustments to Local Friction in Multifinger Prehension. *J Mot Behav* **39**, 276–290 (2007).
5. Johansson, R. S. & Westling, G. Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Exp Brain Res* **56**, 550–564 (1984).
6. Park, J., Baum, B., Kim, Y.-S., Kim, Y. & Shim, J. K. Prehension Synergy: Use of Mechanical Advantage During Multifinger Torque Production on Mechanically Fixed and Free Objects. *Journal of applied biomechanics* **28**, 284–90 (2012).
7. Zatsiorsky, V. M., Gregory, R. W. & Latash, M. L. Force and torque production in static multifinger prehension: biomechanics and control. I. Biomechanics. *Biological Cybernetics* **87**, 50–57 (2002).
8. Olafsdottir, H., Zhang, W., Zatsiorsky, V. M. & Latash, M. L. Age-related changes in multifinger synergies in accurate moment of force production tasks. *J Appl Physiol* **102**, 1490 (2007).
9. Zhang, W., Olafsdottir, H. B., Zatsiorsky, V. M. & Latash, M. L. Mechanical Analysis and Hierarchies of Multi-digit Synergies during Accurate Object Rotation. *Motor Control* **13**, 251–279 (2009).
10. Rajakumar, B. & Skm, V. Comparable behaviour of ring and little fingers due to an artificial reduction in thumb contribution to hold objects. *PeerJ* (2020) doi:10.7717/peerj.9962.
11. Shim, J. K., Latash, M. L. & Zatsiorsky, V. M. Finger coordination during moment production on a mechanically fixed object. *Exp Brain Res* **157**, 457–467 (2004).
12. Rajakumar, B., Dutta, S. & SKM, V. Validity of Mechanical advantage hypothesis of human grasping depends on the nature of task difficulty. (2021) doi:10.21203/rs.3.rs-1058248/v1.
13. Lakens, D. Equivalence Tests: A Practical Primer for *t* Tests, Correlations, and Meta-Analyses. *Social Psychological and Personality Science* **8**, 355–362 (2017).
14. Niu, X., Latash, M. & Zatsiorsky, V. Effects of Grasping Force Magnitude on the Coordination of Digit Forces in Multi-finger Prehension. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale* **194**, 115–29 (2009).
15. Banuvathy, R. & Varadhan, S. K. M. Distinct behavior of the little finger during the vertical translation of an unsteady thumb platform while grasping. *Sci Rep* **11**, 21064 (2021).
16. Wang, K., McGlinn, E. P. & Chung, K. C. A Biomechanical and Evolutionary Perspective on the Function of the Lumbrical Muscle. *J Hand Surg Am* **39**, 149–155 (2014).
17. Johnston, J. A., Winges, S. A. & Santello, M. Neural control of hand muscles during prehension. *Adv Exp Med Biol* **629**, 577–596 (2009).
18. Poston, B., Danna-Dos Santos, A., Jesunathadas, M., Hamm, T. M. & Santello, M. Force-independent distribution of correlated neural inputs to hand muscles during three-digit grasping. *J Neurophysiol* **104**, 1141–1154 (2010).

Figures

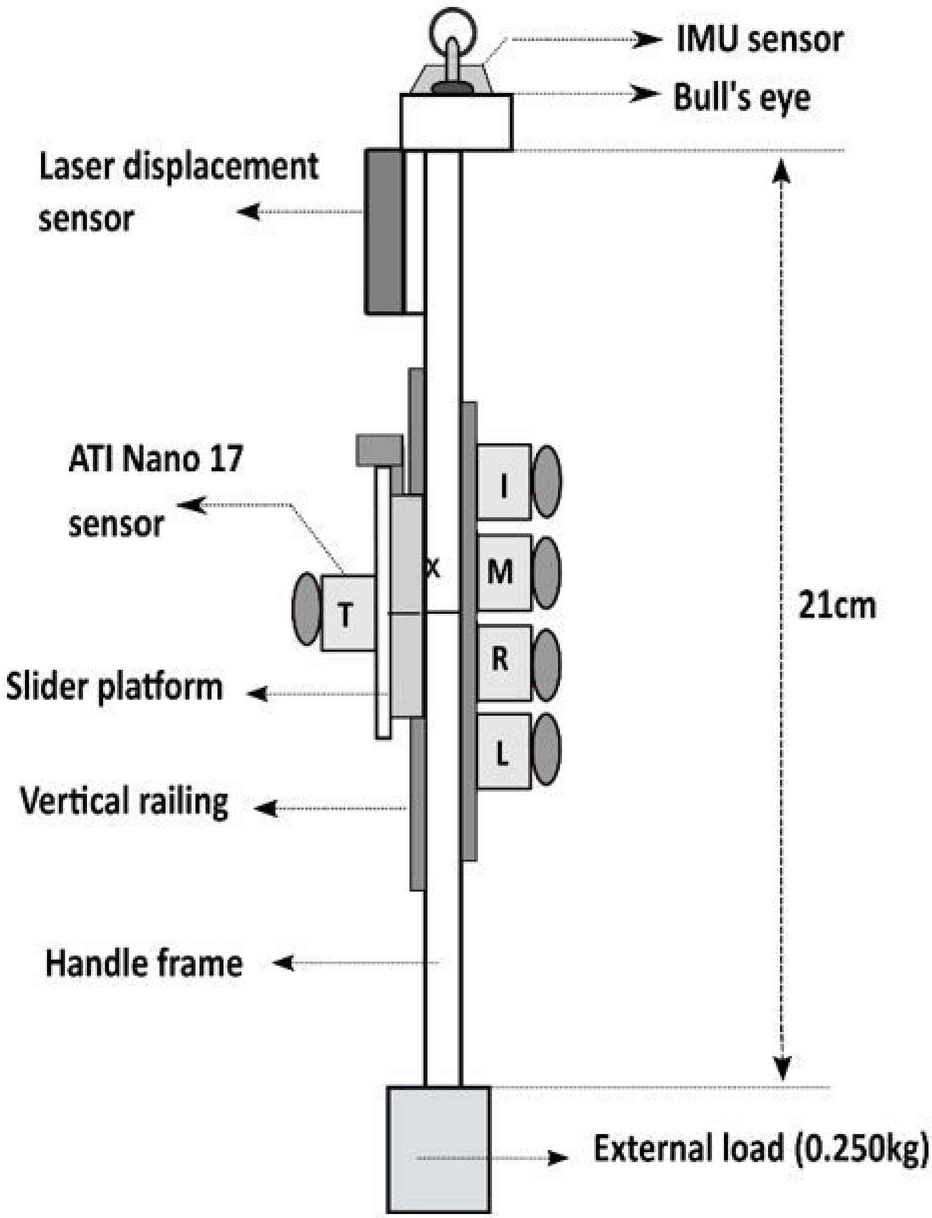

Figure 1

Schematic diagram of the experimental handle The figure shows the schematic diagram of the experimental handle with the slider platform on the thumb side of the handle. The handle was made of an aluminum handle frame (21 x 1 x 3) cm with a slider platform mounted over the vertical railing of length 13.6cm. The mass of the slider platform was 0.100kg. Five six axis force/torque sensors (ATI Nano 17) were mounted on the handle frame to measure the fingertip forces of the individual fingers and thumb. A displacement sensor and an IMU sensor were placed on top of the handle. An external load of mass 0.250kg was attached at the bottom of the handle.The mass of the handle including slider platform and external load was 0.700kg. The distance between the sensor surface of the thumb and other fingers (grip aperture) is 6.2cm.

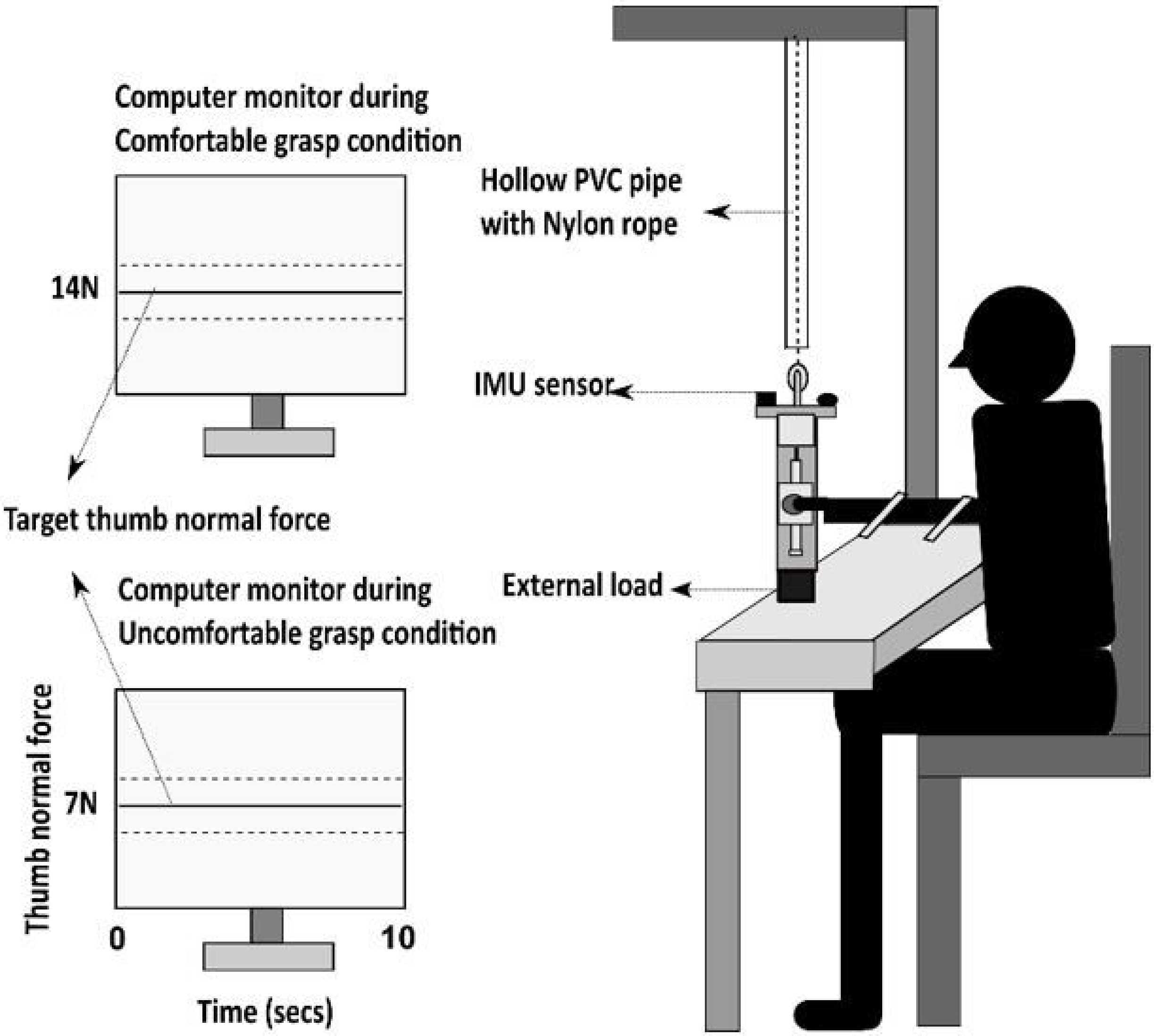

Figure 2

Schematic diagram of the experimental setup The figure shows the experimental setup with a participant holding the experimental handle in front of the computer monitor. The monitor displayed a solid horizontal line that corresponded to the target normal force to be produced by the thumb. During comfortable grasp condition, the solid horizontal line shown on the monitor corresponded to 14N of normal force to be produced by the thumb. Whereas during uncomfortable grasp condition, the solid horizontal line shown on the monitor corresponded to 7N of normal force to be produced by the thumb. The two dashed lines above and below the solid line signify an error margin of ±0.5N.

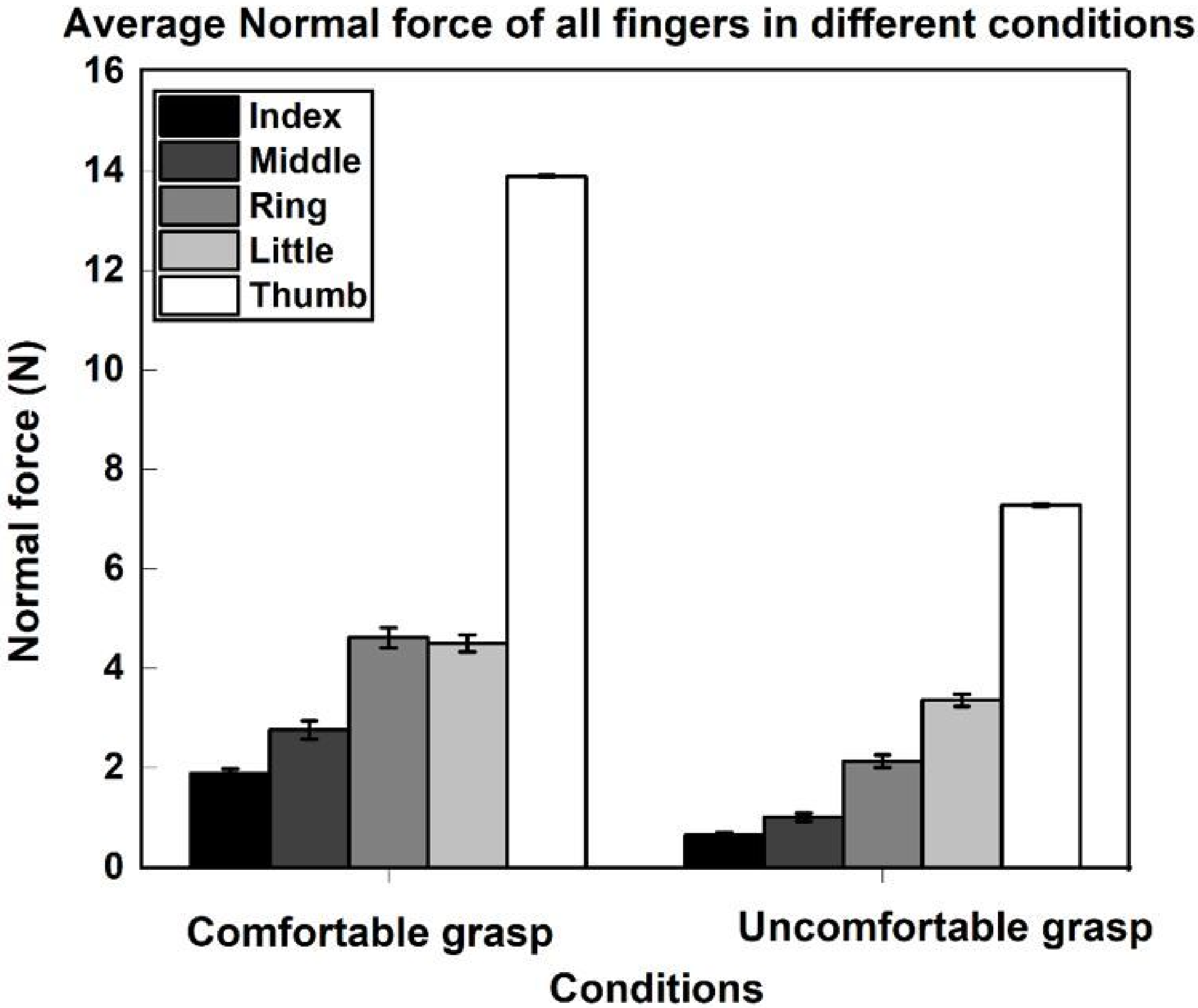

Figure 3

Average Normal forces of the individual fingers and thumb in different conditions. Little finger normal force (represented in light shaded gray) of comfortable grasp condition was statistically equivalent to the ring finger normal force (represented in medium shaded gray) of the same condition. In contrast, during uncomfortable grasp condition, little finger normal force (represented in light shaded gray) was statistically greater ($p < 0.001$) than the ring finger normal force (represented in medium shaded gray). During comfortable grasp condition, the average thumb normal force (Mean = 13.89N, SD = 0.07) produced by the participants was statistically greater ($p < 0.001$) than the average thumb normal force (Mean = 7.28N, SD = 0.09) produced during uncomfortable grasp condition.