DEPARTMENT OF APPLIED MECHANICS
INDIAN INSTITUTE OF TECHNOLOGY
MADRAS
CHENNAI – 600 036

Studies on the applicability of the mechanical advantage hypothesis of grasping

A Thesis

Submitted by

Banuvathy R

For the award of the degree

Of

DOCTOR OF PHILOSOPHY

April 2022

DEPARTMENT OF APPLIED MECHANICS
INDIAN INSTITUTE OF TECHNOLOGY
MADRAS
CHENNAI – 600 036

Studies on the applicability of the mechanical advantage hypothesis of grasping

A Thesis

Submitted by

Banuvathy R

For the award of the degree

Of

DOCTOR OF PHILOSOPHY

April 2022

"A journey of thousand miles begins with a single step"

- ***Lao Tzu***

To my family

THESIS CERTIFICATE

This is to certify that the thesis titled **Studies on the applicability of the mechanical advantage hypothesis of grasping** submitted by me to the Indian Institute of Technology, Madras for the award of the degree of **DOCTOR OF PHILOSOPHY,** is a bona fide record of research work carried out by me under the supervision of Dr Varadhan SKM. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Chennai 600 036 **Research Scholar**

Date : Wednesday, 06 April 2022

Research Guide

LIST OF PAPERS BASED ON THIS THESIS

REFEREED JOURNALS BASED ON THIS THESIS

1. Banuvathy Rajakumar and Varadhan Skm., (2020) *Comparable Behaviour of Ring and Little Fingers Due to an Artificial Reduction in Thumb Contribution to Hold Objects*, PeerJ, 8:e9962, doi: 10.7717/peerj.9962, Open Access, Indexed by Scopus, WOS.

2. Rajakumar Banuvathy and SKM Varadhan, (2021) *Distinct behavior of the Little Finger during the vertical translation of an unsteady thumb platform while grasping*, Scientific Reports, 11(1):21064, doi: 10.1038/s41598-021-00420-5, Nature publishing group, Open Access, Indexed by Scopus, WOS.

PUBLICATIONS IN CONFERENCE PROCEEDINGS

1. Rajakumar Banuvathy and SKM Varadhan., *Comparable Safety Margins of the Ulnar fingers when the thumb remains on an unsteady slider*, Proceedings of VSAM 2021 (yet to be published by Springer Nature- SCOPUS indexed)

ACKNOWLEDGEMENTS

First and foremost, I feel grateful to God for his immense blessings to accompany me in all the ups and downs during these years. I would like to express my sincere gratitude to my research adviser Dr.Varadhan SKM for his continuous support, valuable feedback, and patience during my entire research journey at IIT Madras. His encouragement and thoughtful advice at every stage of my research have made me evolve as an independent thinker.

I want to extend my heartfelt thanks to my Doctoral committee members Dr C. Lakshmana Rao, Dr. Shaikh Faruque Ali and Dr. Ganapathy Krishnamoorthy for their honest comments to improvise my research in every possible way. Further, I would like to thank my lab senior researcher, Dr. Dhanush Rachaveti, for his friendship, support, and motivation at every stage of my research. I always remember and cherish the companion of Akash and Ann David for their constant encouragement and endless support in motivating me during all my downfalls.

I thank my fellow lab mates Vaisakh, Vignesh, Anurag, Prajwal, Swarnab, Jayseelan, Thomas, Eswari, and Rakhi, for their kindness in sharing their opinion and feedback on my research during the lab meetings. I would like to thank the Women Leading IITM team for granting fellowship to pursue my research work.

BANUVATHY R

ABSTRACT

KEYWORDS: Object stabilization, Mechanical advantage, Grasping, Ulnar fingers

The human hand plays a vital part in performing daily life tasks. Grasping is one of the everyday activities performed by humans. Object stabilization while grasping is essential for the safe handling of the grasped object. Individual fingertip forces adjust in a coordinated manner to stabilize the grasped object. The contribution of the individual fingers was investigated when the grasped object undergoes systematic changes (or perturbation) such as changes in the external torque, load, grip width, friction, and individual digit width. However, the current research focused on examining the involvement of ulnar fingers (ring and little) when torque changes were introduced by artificially reducing the thumb contribution to hold the object.

In the first experimental study, the participants were instructed to hold the slider platform steady at the HOME position (midway between middle and ring fingers). Ulnar finger normal forces increased to produce the compensatory supination moment. According to the mechanical advantage hypothesis (MAH), fingers with longer moment arms for normal force produce greater normal force than fingers with shorter moment arms during the moment production task. Although the little finger has a longer moment arm than the ring finger, it produced a statistically equivalent normal force to the ring finger. A natural question that emerged from the first study results was whether the applicability of the mechanical advantage hypothesis depends on employing heavy masses while grasping. With the addition of external loads of masses 0.150, 0.250, and 0.350 kg, ulnar finger normal forces systematically increased but were statistically

comparable with each other. However, MAH was supported when an external load of a larger mass of 0.450kg was added. It was suspected that the task difficulty or individual’s ability of managing a task due to the addition of heaviest external load (comparatively greater than the other masses) would have would have caused to prefer employing the mechanical advantage principle. Further, an experiment was performed to confirm that a task difficulty would trigger to opt for the strategy of mechanical advantage hypothesis. In addition to the restriction on the thumb’s tangential force and position, the restriction was also imposed to produce minimal normal force. Therefore, in the study that required minimal normal force, little finger normal force was greater than the ring finger normal force.

Followed by this study, the peripheral fingers (index and little) contribution was examined to understand their role in establishing the static equilibrium when the thumb platform undergoes vertical motion to trace the trapezoid and inverted trapezoid pattern displayed on the monitor. The distinct behavior of the little finger compared to the other finger forces perhaps suggests a biomechanical relationship between thumb and little finger. Further, with the downward translation during inverted trapezoid pattern tracing, there was a restriction in the range of motion of the Carpometacarpal joint (CMC) joint of the thumb. Due to this biomechanical constraint, the task of maintaining the platform at a level below the center of the ring finger sensor was quite challenging. Hence, it was believed that the mechanical advantage hypothesis's applicability depends not merely on the moment arm of the suspended load or mass of the handle but the difficulty associated with the task situation. This could have been the primary reason for the system to use the little finger's mechanical advantage.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY

The following are some of the commonly used terms in the thesis:

Peripheral fingers	Index and little fingers
Central fingers	Middle and ring fingers
Ulnar fingers	Ring and little fingers
Radial fingers	Index and middle fingers
Small finger	Little finger
Grip force	Normal force
Load force	Tangential force

ABBREVIATIONS

CNS	Central Nervous System
MAH	Mechanical Advantage Hypothesis
CMC	Carpometacarpal
FDP	Flexor Digitorum Profundus
ANOVA	Analysis of Variance
PIP	Proximal interphalangeal
DIP	Distal interphalangeal
COM	Center of mass
VF	Virtual finger
VFTH	Virtual finger-Thumb
SM	Safety margin
EV	Elemental variables
PV	Performance variable
SEM	Standard error of mean
LDA	Linear Discriminant Analysis
RMSE	Root Mean Square Error
TOST	Two one sided t-tests
NF	Normal force
TF	Tangential force
COP	Center of pressure
MVC	Maximum Voluntary Contraction
SD	Standard Deviation

NOTATION

ΔV	Index of covariation
Δ_L	Lower equivalence bound
Δ_U	Upper equivalence bound
SM_z	Z- transformed Safety margin

CHAPTER 1.

INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

Generally, during the manipulation of any object, fingers and thumb of the human hand contribute remarkably for the safety of the grasped object. Among the various tasks employed by the human hand, grasping an object is the most common task performed by healthy human beings. Our central nervous system (CNS) plays a vital role in systematically controlling the fingers and thumb movements while performing the grasping task.

Predicting the mass of an object, pre-shaping the fingers and thumb based on the structure of the object, reaching to the object, and holding with the appropriate grasping forces are the stages to be accomplished for fine grasping. Many a times, the object held in hand has to be maintained stable for the successful completion of the task. Grasp stability is attained by finely controlling the forces exerted by the individual fingers and thumb in an organized way. Compared to all the fingers in the human hand, the role of the thumb is exceptionally significant. Without the thumb, grasping an object becomes difficult and inefficient. Proper positioning of the thumb on a grasped object helps to maintain the object stable.

Any systematic variation (or perturbation) to the grasped object results in complete modification of the finger mechanics for sustaining the object stability. In this research work, such modifications in the pattern of the individual fingers and thumb forces were investigated when the thumb was placed on an unsteady platform. Since there occurs a torque change to the grasped object, it was expected that fingers with longer moment arms for normal force contribute greatly to establish the static equilibrium of the handle (mechanical advantage hypothesis). The current research investigates the validity of this hypothesis under various conditions. The outline of the thesis has been discussed below.

1.1.1 Outline of thesis

1. Introduction and Literature review- This chapter gives a brief overview of the hand anatomy, the need to study the human hand, motor redundancy problem, prehension, and mechanical advantage hypothesis. It will be then followed by the literature survey on the prehensile tasks.

2. Study of fingertip force distribution when the thumb was placed on the unsteady platform- The second chapter describes how the finger force redistributes to establish the object stabilization when the thumb platform was unconstrained (free) at the home position compared to the constrained (fixed) condition. The chapter also explains the chain effects which were observed during the free condition.
3. Study of fingertip force distribution when the thumb was placed on the unsteady platform and mass of the handle was systematically increased. The third chapter will give details on how the ulnar finger (ring and little) forces varied when the mass of the handle was systematically increased. This chapter also explains whether the applicability of the mechanical advantage hypothesis is task-specific and briefly explains the kind of task that supports this hypothesis.

4. Study of fingertip force distribution during uncomfortable grasp of producing lesser normal force by the thumb while holding the handle with unsteady thumb platform. The fourth chapter explains the task that induces to choose the mechanical advantage principle for re-establishing handle equilibrium.
5. Modulation of individual fingertip forces and moments while tracing trapezoid and inverted trapezoid patterns by displacing the thumb platform vertically. The fifth chapter provides information on how the peripheral fingers (index and little) varied their forces to compensate for the torque caused during the upward and downward shift of the unsteady thumb platform. This chapter also explains the biomechanical inter-relationship between the thumb and little finger.
6. The final chapter will include the summary of the thesis, future direction and limitations.

1.1.2 Why do we study the human hand?

It is an interesting question to investigate how the brain works while learning a task, making a movement, choosing an option, etc. Among all the functionalities of the central nervous system (CNS), the most remarkable and measurable outcome of the CNS are the movements. In the brain, the motor cortex serves to control the voluntary movements of the human body. Generally, there are various kinds of movements performed by humans. It includes movement of the head, lip, eyelid, upper limb, lower limb, etc. Movements in these body parts are activated by the neuronal projections from the motor cortex as shown in Figure 1.1.

Among all the body parts that possess the ability to move, hands and fingers have direct monosynaptic projections from the motor cortex to the alpha motoneurons that connect to the hand muscles. In contrast, the legs and toes have several interneurons found in between. Hence, the hand and fingers can be used as a model system to understand the human movement control system. The cortico-neurons from the motor cortex project to the alpha-motoneurons that innervate the muscles controlling hands and fingers [1]. Therefore, the movements performed by the distal parts of the fingers help to provide information regarding the strategy followed by the CNS to accomplish a task.

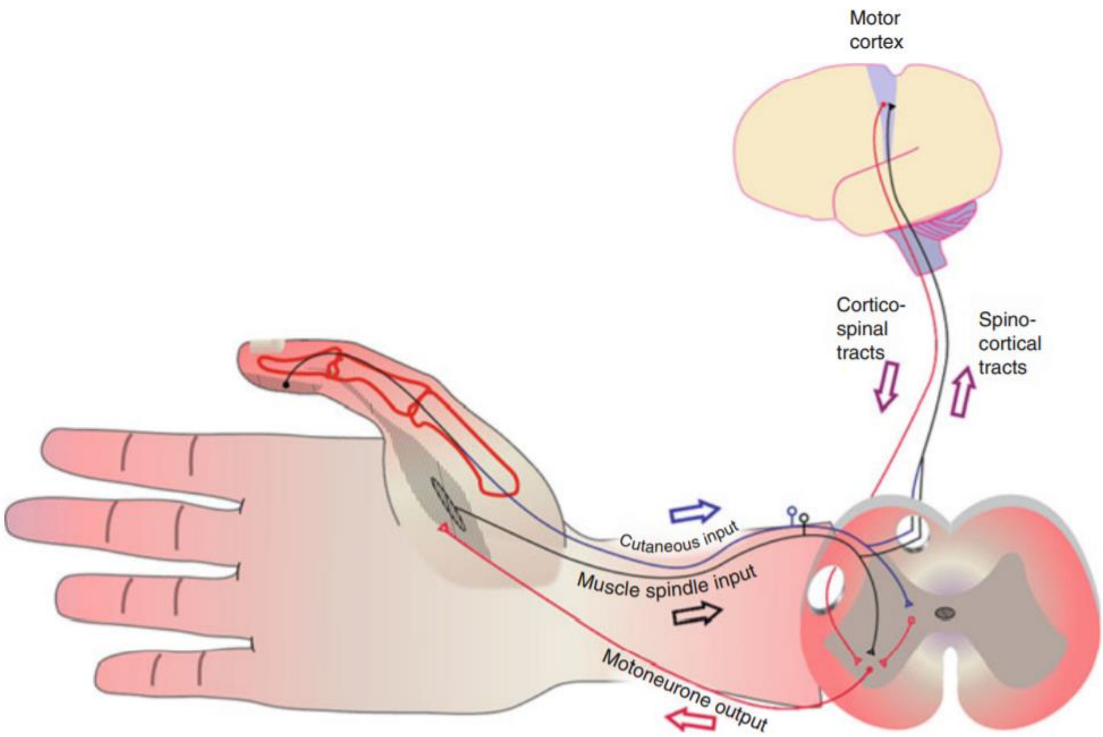

Figure 1.1 Input and Output neuronal connections of motor cortex. Proprioceptive and cutaneous inputs from the hand were carried to the motor cortex via the spinal cord. The afferent sensory signals travel to the spinal inter-neurons, then through the spino-cortical tracts, sensory input is carried to the motor cortex. The cortico-spinal projections from the brain project to the lower (alpha) motorneurones supplying the distal hand muscles. Thereby causing a motor function in the hands and fingers. (figure adapted from the chapter of a book titled *Neuroscience in the 21st century* (pp:1326), Pfaff 2013, published by Springer [2])

1.1.3 Human hand anatomy

The human hand is a fascinating organ that evolved from a structure of locomotion to an organ accountable for manipulation and exploration. The anatomy of the hand includes bones, muscles, joints, intricate nerves, and blood supplies. Each will be elaborated in detail in the below paragraphs.

1.1.4 Muscles of the hand

Hand muscles are composed of two different groups: intrinsic and extrinsic muscle groups. Muscles controlling the movement of the hand are found in the forearm and are known as extrinsic hand muscles. It includes both flexor and extensor muscles of the wrist and hand. These muscles originate from the bones in the arm and extend as tendons in the wrist.

Flexors are located along the anterior portion of the forearm. Flexor pollicis longus is responsible for the flexion of the interphalangeal joint of the thumb. While, Flexor digitorum profundus is accountable for the flexion of distal interphalangeal (DIP) joints of the index, middle, ring, and little fingers [3]. Flexor digitorum superficialis is responsible of the flexion of the proximal interphalangeal (PIP) joint of each finger. Flexor carpi ulnaris, Flexor carpi radialis, and Palmaris longus are involved in the flexion of the wrist joint.

Extensors arise from the ulna and extend to the dorsal side of the fingers. These muscles are located inside six different compartments. The first compartment includes the tendons of abductor pollicis longus and extensor pollicis brevis. The second compartment contains the tendons of extensor carpi radialis brevis and longus. Extensor pollicis longus is in the third compartment, whereas extensor indicis proprius and extensor digitorum communis are in fourth compartment.

Intrinsic muscles are the ones that have origin and insertion within the hand (see Figure 1.2). There are four groups of intrinsic muscles. They are three thenar muscles- flexor pollicis brevis, abductor pollicis brevis, and opponens pollicis covering the thumb and metacarpals, responsible for pronating the thumb and raising the thumb straight [4].

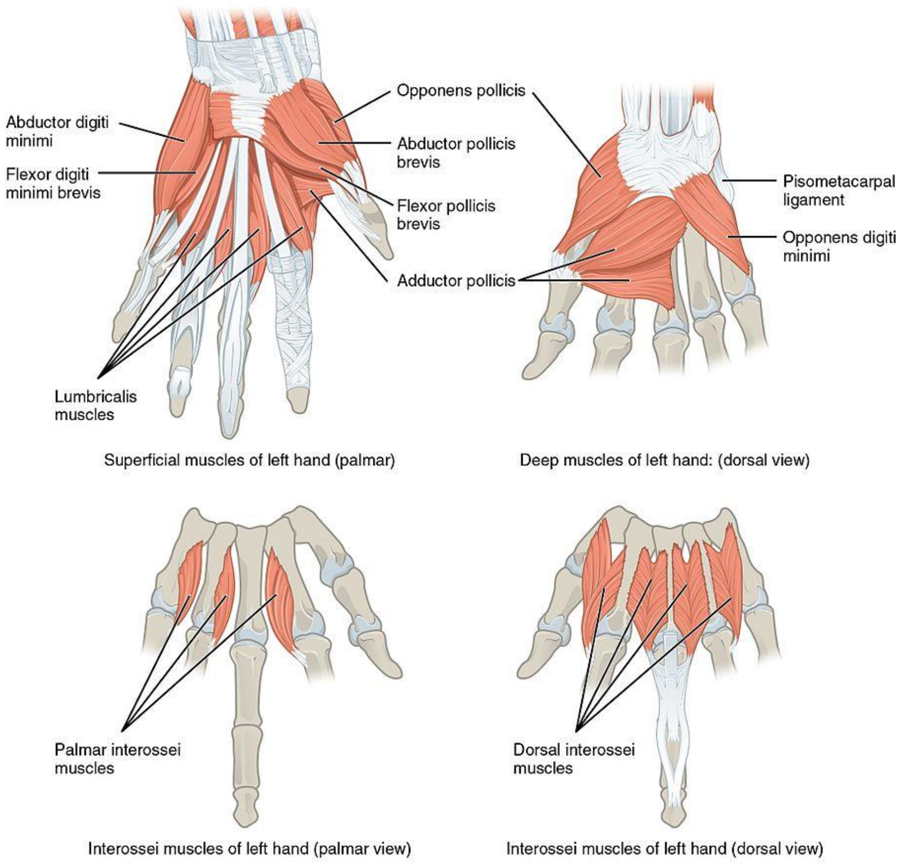

Figure 1.2 Intrinsic muscles of the hand. The figure shows the origin and insertion of the intrinsic muscles such as the thenar, hypothenar, lumbrical, dorsal, and palmar interossei of the hand. The upper row of the figure includes hypothenar and thenar muscles. The lower row of the figure shows the interossei muscles of the hand (figure adapted from the paper titled *Role of Morphology of thumb in Anthropomorphic Grasping: A Review* by

Nanayakkara et al. 2017, published by Frontiers in Mechanical Engineering [5])

Three muscles of hypothenar eminence- opponens digiti minimi, flexor digiti minimi and abductor digiti minimi, cause flexion and abduction of the little finger. Four lumbrical muscles help to flex the metacarpophalangeal joint of the fingers and extension of the interphalangeal joint. Three palmar interosseous muscles involve in abducting and adducting fingers. The functions of the individual muscle group of the hand have been explained in the tabular column (see Table 1.1).

Table 1.1 Intrinsic muscles of the human hand with their function

MUSCLE	**MUSCLE GROUP**	**FUNCTION**
Dorsal interossei (4)		spread fingers away
Palmar interossei (3)		pull fingers together
Hypothenar muscle group	Abductor digiti minimi	pull little finger away from ring finger
	Flexor digiti minimi	bend metacarpal joint of little finger
	Opponens digiti minimi	bring little finger towards thumb

Thenar muscle group	Abductor pollicis brevis	pull thumb away from index finger
	Flexor pollicis brevis	bend thumb toward the little finger
	Opponens pollicis	move thumb towards others finger
Lumbricals		straighten the fingers

1.1.5 Bones and Joint

The hand consists of 27 bones: eight carpal bones for the wrist, five metacarpals, and fourteen phalangeal bones. Carpal bones form two rows: proximal and distal row (see Figure 1.3). These bones are held tightly together by the ligaments. The proximal row includes pisiform, triquetrum, lunate and scaphoid. The distal row comprises of hamate, capitate, trapezoid and trapezium. Two carpal bones (scaphoid and lunate) and the radial bone from the forearm form the lower part of the hand, which helps primarily for hand movements. Further, five metacarpal bones articulate with the carpal bones in the distal row[6]. The thumb's metacarpal bone and one carpal bone (trapezium) from the distal row combine to form a carpometacarpal joint of the thumb. This basal joint of the thumb is saddle-shaped that makes the thumb more flexible. The carpometacarpal joints are capable of radial/ulnar deviation and flexion/extension movements. Further, the metacarpophalangeal joints are the condyloid type involved in flexion, extension, abduction, adduction, and circumduction.

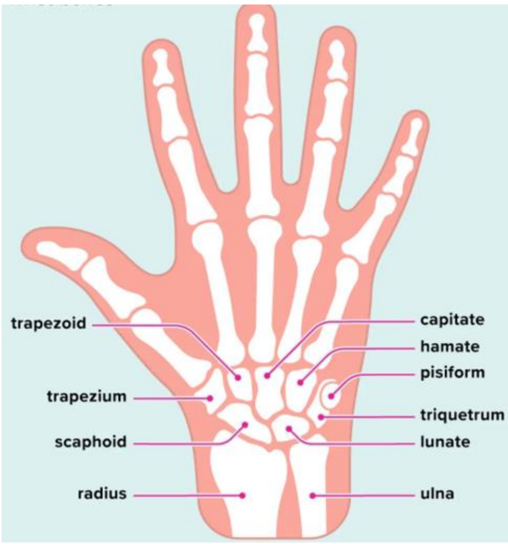

Figure 1.3 Carpal bones of the human hand. The proximal and distal row of carpal bones are shown. (Image credit: https://www.healthline.com/health/wrist-bones)

1.1.6 Nerve supply to the hand

Three nerves innervate the human hand. They are radial, ulnar, and median nerves that innervate particular regions in the human hand, as shown in Figure 1.4. The median nerve is a major nerve in the upper limb of humans, that rises from the branches of the brachial plexus that originates from the ventral roots of cervical vertebrae C5-C7, C8, and T1[7]. It innervates the pronator and flexor muscles in the anterior compartment of the forearm (except flexor digitorum profundus and flexor carpi ulnaris). The same nerve conveys sensory stimulus from the skin over the thenar eminence, lateral palm, dorsal and palmar side of the lateral fingers.

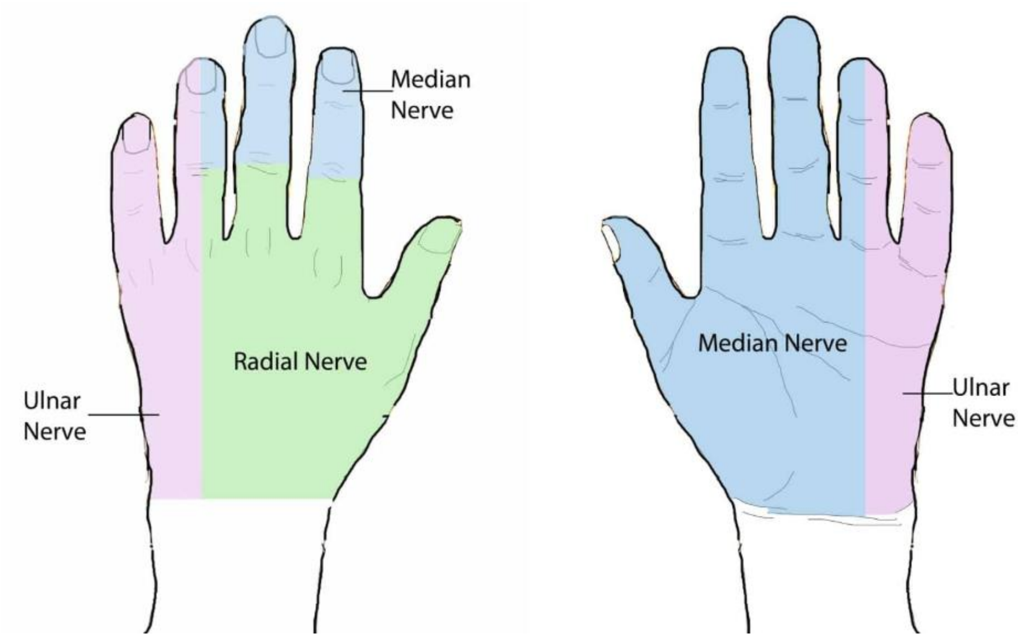

Figure 1.4 Areas of cutaneous innervation in the human hand. Nerves supplying human hand and the corresponding areas associated (Image credit: https://geekymedics.com/anatomy-of-the-hand/)

The radial nerve and its branches innervate the dorsal arm muscles (triceps brachii and anconeus) and extrinsic extensor group of muscles. The radial nerve carries sensory stimulus from the posterior arm, forearm, lateral dorsum of the hand, and proximal dorsal aspect of the lateral fingers (thumb, radial fingers, and half the ring finger). The ulnar nerve innervates the flexor muscles of the forearm, such as flexor digitorum profundus and flexor carpi ulnaris. In addition to this, ulnar nerve innervates the intrinsic muscles of the hand except thenar muscles and two lateral lumbricals. The ulnar nerve conveys sensory information from the small finger (otherwise called as little finger), half of the ring finger, and their palm area.

1.1.7 Blood supply to the upper arm and hand

The heart pumps oxygenated blood via the aorta to the upper arm through the left and right subclavian arteries that flow beneath the collar bones. Axillary arteries that branch from the subclavian artery supply blood to the upper arm. The brachial artery branches into the radial and ulnar artery in the forearm region. The radial artery, which is found superficial to the radial bone, supplies oxygenated blood to the lateral side of the forearm and wrist. The ulnar artery supplies blood to the medial side of the forearm, and it is found above the ulnar bone. Radial and ulnar arteries combine to form superficial and deep palmar arches, which later branch to form small arteries like palmar digital arteries and palmar metacarpal arteries. These small arteries supply blood to the palm and fingers.

1.2 LITERATURE SURVEY

The human hand grasps an object through a variety of grips. Depending on the object’s structure, shape, and mass, the grasp type may vary. For better stability, the prismatic precision grip is employed where each finger produces three-dimensional force and three-dimensional moment components. As a result, five fingers grasp need thirty force and moment components (that means thirty degrees of freedom) to describe any mechanical action.

However, only six degrees of freedom are required to hold a rigid object static in the air. Since the degrees of freedom of multi-digit grasps exceed a solid object's degrees of freedom, thirty unknown variables are involved in solving six equations. As the number of variables is higher than the number of equations, an infinite number of solutions are possible. This is the motor redundancy problem [8]. The common question raised by most researchers is to know how the CNS addresses this motor redundancy issue and how it chooses a particular solution from the infinite sets of all possible solutions by the redundant multi-finger grasp. Therefore, Multi-digit grasps are considered to be a mechanically redundant system. Multi-finger prehension serves as the best example to study the famous motor redundancy problem [9]. Under which situation or condition, the CNS chooses a particular solution from the pool of numerous solutions is the topic of interest for the current research. Hence, multi-finger grasping was chosen to explore further.

1.2.1 Multi-finger prehension

Historically, research had been carried out in understanding the variation of normal forces in individual fingers and thumb while grasping an object. A vast number of studies examined the strategy followed by the controller in controlling the normal and tangential forces at various conditions or constraints introduced to the handheld object. Followed by the two-finger precision grip, studies were also carried out with three-digit grasping [10] and four-digit grasping [11].

The act of reaching, grasping, and manipulating an object with hand and fingers is called prehension. The basic steps involved in the interaction with the object include reaching the object and holding it stable. There are three phases of grasping: Pre-grasp, Static grasp, and manipulation [12]. The pre-grasp phase encompasses hand transportation and hand pre-shaping. The static grasp phase involves holding the object static in the air, while the manipulation phase incorporates the hand motion for the purposeful handling of the object. There is a large volume of published studies describing the contributions of individual fingers and thumb during five-finger grasping (so-called multi-finger prehension) when the center of mass [13], grip aperture [14], and the frictional condition [15] is altered.

Multi-finger prehension involves the participation of all fingers and thumb. The stability of the multi-finger prehension of an object held static in the air is attained by satisfying the following three equations. To achieve static equilibrium in the horizontal and vertical direction, equation (1.1) and (1.2) has to be satisfied. For attaining rotational equilibrium, equation (1.3) has to be satisfied.

$$F_n^I + F_n^M + F_n^R + F_n^L - F_n^T = 0 \tag{1.1}$$

$$F_t^I + F_t^M + F_t^R + F_t^L + F_t^T = W \tag{1.2}$$

$$F_n^I d^I + F_n^M d^M + F_n^R d^R + F_n^L d^L + F_n^T d^T + F_t^I r^I + F_t^M r^M + F_t^R r^R + F_t^L r^L + F_t^T r^T = 0 \tag{1.3}$$

where the superscripts I, M, R, L, and T refer to index, middle, ring, little, and thumb, the subscripts t and n refer to tangential and normal force components. W refers to the weight of the object. The coefficients r and d stand for moment arms of tangential and normal force with respect to the center of the object. In static equilibrium, the vector sum of the moment due to grip (or normal) forces and moment due to load (or tangential) forces should be equal to external torque acting on the object. In the first equation, forces are balanced in the horizontal direction, and in the second equation, forces are balanced in the vertical direction.

In the case of prismatic precision grip, grip forces of all the fingers act perpendicular to the plane of grasp. All the fingers opposing the thumb is collectively called virtual finger (VF) [16], which generates the same mechanical effect similar to that of the actual fingers. At the zero-torque task condition, it is well known that the sum of the tangential moment and the normal moment is equal to zero for the handle at static equilibrium. In the non-zero torque condition, the sum of the tangential moment and the normal moment is equal to the total moment (refer equation 1.4).

$$M_n + M_t = Total\ Moment \tag{1.4}$$

1.2.2 Force sharing

Several researchers have been investigating the force sharing among the fingers and thumb during multi-finger prehension over the years [17]–[22]. The amount of force shared by each finger depends on the orientation of the object [23], the task performed, and the location of the thumb [24]. During the moment production task, while holding a handheld object, depending on the direction of the moment, the fingers act either as force agonists or antagonists [25]. Suppose if there is a requirement to produce a pronation moment, the index and middle finger act as agonists (occur in the intended direction) while the ring and little finger act as antagonists (occur in the opposite direction). On the other hand, if it is a supination moment production task, the ring and little finger act as agonists, whereas the index and middle act as antagonists.

Previously, studies have attempted to explore the force contribution of individual fingers in grip strength exertion tasks. It was found that the forces exerted by the index and middle finger were found to be higher than the forces produced by the ring and little [17]. Among the index and middle finger, the ability to exert greater tangential force was the middle finger [18]–[20], [26]. During the task which involved gripping, lifting, and holding of a five-finger prehensile handle [27], the percentage share of grip forces of thumb, index, middle, ring, and little were 50.0, 15.4, 14.6, 11.7, and 7.3% while the vertical tangential forces were 39.4, 9.9, 19.3, 14.0 and 17.5%. Next to the thumb, the % share of the tangential force of the middle finger was greater, which was then followed by little, ring, and index finger. One notable point in this study was the location of the thumb. The thumb was positioned exactly opposite to the center of the middle finger force sensor rather than between the middle and ring fingers.

A study investigated tangential load sharing among fingers during the prehension of five-finger handle, which was loaded both in the upward and downward direction [28]. In addition to the loading direction of the handle, the grip aperture of the handle was also varied. And the tangential force sharing among the fingers was different in each case. These results convey no standard tangential load force contribution for the individual fingers; the sharing percentage varies with the task performed. Normal and tangential force sharing among fingers was computed for different external torque conditions in either direction in a moment production study [29]. The percentage share of the tangential force for the index finger was greater than the other fingers for the pronation moment tasks, while the tangential force share was greater for the little finger than the other fingers in supination moment tasks.

In a prehension study [24], the total shear force was computed while holding an instrumented handle by having the thumb opposed at seven different positions from the index finger level to the little finger level. While, in another prehension study by [30], the location of the thumb was varied in a discrete manner to three different positions (upper, middle, lower). Thumb tangential force varied significantly for different positions of the thumb. The thumb's load force decreased while the thumb was held at the upper position and increased while the thumb was held at the lower position. In the above studies, tangential force sharing of the other individual fingers was not investigated in great detail when the location of the thumb was altered while grasping. The current research aimed to fill this gap of understanding the individual finger's tangential force contribution when the tangential force of the thumb is kept constant at different location of the thumb. Therefore, the experimental handle for the current research was designed in such a way to explore the tangential force sharing in the other fingers by maintaining the thumb's load contribution as constant.

1.2.3 Mechanical advantage hypothesis

Data from the previous studies have shown evidence that the middle and ring finger plays a vital part in supporting the mass of the object, while the index and little finger contribute in producing rotational action. Thus, the middle and ring fingers ("central fingers") are called the load-bearing fingers, whereas the index and little fingers ("peripheral fingers") are called the moment or torque generators [9], [25], [30]. Forces produced by the central fingers depend only on the external load applied, while the forces produced by the peripheral fingers depend both on the external load and torque [25]. The facts about the peripheral and central fingers led to the formulation of the Mechanical advantage hypothesis.

With reference to the Mechanical Advantage hypothesis, during the pronation or supination moment production tasks, the index and little finger tend to produce greater normal force than the middle and ring finger. As the peripheral fingers have longer moment arms with respect to the thumb as pivot compared to the central fingers, they tend to produce higher normal force. This hypothesis was supported in the studies that involve the static moment production tasks [13], [25], [31]–[35] except the study on finger force arrangement during torque production on a object that is fixed mechanically [29]. The findings of the latter study were only in partial agreement with the mechanical advantage hypothesis. The reason could be because the participants were instructed to produce a specific target moment by grasping a mechanically fixed object, while, in other static moment production tasks, the participants were instructed to overcome the external torque for maintaining the rotational equilibrium. The authors assumed that the applicability of the Mechanical advantage hypothesis is task and effector specific in nature.

In another grasping study [32], the participants were made to make vertical cyclic arm motions with the five-finger prehensile handle held in hand and the load suspended at different positions, causing different external torques. The results of the study corroborate the mechanical advantage hypothesis confirming the significant contribution of peripheral finger forces in object manipulation.

A similar kind of handle, however, with the horizontal beam in the anterior-posterior direction was employed in the prehension study [13], with the only exception of having external torque acting in the direction perpendicular to the plane of grasp. The task involves the static holding of the handle by performing radial or ulnar deviation to counteract the external torque. The grip force exerted by the index and little was greater compared to the normal force magnitude exerted by middle and ring to compensate for the external torque. Moreover, the above studies introduced external torque by suspending load on the beam, and individual fingers produced compensating moments to counterbalance the external torque. Furthermore, in the pressing task [35], the mechanical advantage hypothesis (MAH) was investigated to appreciate the contribution of peripheral fingers in producing the required moment of force.

Zatsiorsky and his colleagues [25] experimented using a five-finger prehension handle with a horizontal beam attached at the handle bottom. In each trial, a load of specific mass was suspended on the beam at a particular distance from the center of the handle. The task was to produce either pronation or supination moment to overcome the external torque to establish the handle's static equilibrium. Interestingly, there was a monotonic (non-linear) relationship between the moment arm of the finger and the force produced by that finger. The index finger exerted higher normal force than the middle finger during the pronation moment (rotation in anti-clockwise direction). Likewise, the little finger produced higher grip force than the ring finger during the supination moment (rotation in the clockwise direction).

According to some studies [25], [29], supporting the mechanical advantage principle is one of the strategies employed by CNS to economize the effort in moment production tasks while grasping. If the mass of the suspended load is higher, the compensatory moment required to establish equilibrium also increases. For a suspended load of a larger mass 2kg at a distance of 1.9cm from the center of mass of the handle, MAH was not supported. However, when the magnitude of the compensatory moment required is increased systematically by raising the moment arm for the same load 2kg, the little finger produced greater normal force than the ring finger [25].

Similarly, in the case of multi-finger grasping study [36], MAH was supported when a load of 0.150kg (less than 2kg) suspended at a distance of 9.5cm from COM of the handle. So, does this mean, irrespective of the suspended load of any mass, moment arm of the suspended load plays a role in supporting MAH? To answer this question, one of the studies in the current research involved testing MAH when the mass of the suspended load varied systematically with the moment arm of the suspended load as zero (i.e, load suspended below the center of mass of the handle). Fundamentally, from all the above studies, it was not obvious what factor or situation or the kind of task that causes CNS to employ mechanical advantage principle. In the current research, the type of task that lend support to MAH was explored. One of the current studies focused on investigating the underlying factor that kindles CNS to prefer the strategy of employing the mechanical advantage principle during moment production tasks.

1.2.4 Perturbation studies

The forces generated by the fingers during any kind of manipulation with the handheld object serve as a guide for assessing the severity of the human hand disorders and for rehabilitation purposes to enhance the design of the ergonomic robotic hand [37]. The basic activity performed by the human hand is to grasp. Although grasping appears simple, the central controller requires a number of processing details and controlling commands for successful execution.

The objects used in real life are not always similar in their appearance, shape, size, mass, orientation, texture, etc. Different objects have different kinds of physical characteristics. To study the behavior of the fingertip force modulation while handling such objects, researchers designed handles of various grip configurations, and the physical aspects of the handles were modified to mimic the real-life objects. A series of studies were performed with five finger prehension handle when there were changes imparted to the object orientation [28], [38], weight [39], [40], friction [41]–[43], and external torque [25], [30].

Similarly, when there is an expansion or contraction of a handheld object or change in the individual digit width of the grasped object, there will be a readjustment of grip and load forces of the fingers and thumb to re-establish static equilibrium. There emerged a question of whether a local or synergic strategy is followed to retain the equilibrium when there is a change to the entire handle width or individual digit width of the handle. Therefore, a custom-made motorized handle was designed by Zatsiorsky and his colleagues [14] to study the adjustment of fingertip forces & moments during the increase or decrease of the handle width at three different speeds. Also, a load of specific mass was suspended at varying distances on the bar fitted at the base of the handle. It was found that the grip forces raised with the rise in the grip width and decreased with decrease in the grip width. While the thumb load force raised with the increase in the grip width and dropped with decrease in the grip width. The cause-and-effect relations due to the change in handle width was examined. In the trials that required supination moments, equilibrium was established by changing the moment due to grip forces. CNS employed a solution of altering all finger forces (except resultant tangential force) rather than approaching the issue with a local solution of altering tangential forces of the specific finger.

Further, a study was performed to examine how the modification in the moment arm of the load force of a single-finger affects the forces and moments exerted by that finger and the other fingers [34]. There occurs a rise in the tangential force of the perturbed finger with the increase in the tangential moment arm of any individual digit. In that case, it indicates that the tangential forces are under active neural control. If there is a decrease in the tangential forces when the tangential moment arm increases, then it is said to follow the equation of static equilibrium, which was considered a local strategy. However, the study involved in increasing the tangential force of the displaced finger, which means that the central controller actively adjusts the tangential force of the perturbed finger. Consequently, to maintain the rotational stability, normal forces of the other fingers co-adjust, thereby employing a synergic strategy (global).

Additionally, there were also studies performed when the contact location of the individual fingers and thumb on the object varied. There were situations where the contact points of the individual fingers on the object may vary, causing instability in the handheld object. In some cases, it might even result in the dropping of the object from the hand. Hence, it is always interesting to know how the fingers and thumb adapt or adjust themselves to establish stabilization when the contact location of any finger or thumb changes. In a large longitudinal study investigating the force and moment changes between young and elderly adults, the moment arms of the peripheral finger forces were increased along with the external torque changes to the handle [44]. According to the study results, tangential and moment components of the internal forces increased for the elderly; however, there was no rise in the safety margin of the elderly participants during the changes implemented to the grip configurations and torques as expected.

Similarly, the force sharing pattern in the multi-finger task was examined when the thumb contact position varied to seven different discrete locations in the grasp plane [24]. Four uni-directional piezoelectric sensors were employed to obtain the normal force data from all the fingers except thumb. Index finger grip force was higher when the thumb was placed at the index finger end (L0). Tangential force in each finger and thumb grip force were not recorded. However, the total shear force was computed from the moment due to normal force and the grip-width of the handle. The highest total grip force was observed when the thumb was placed at the centre of the handle.

A study to understand the modification in finger forces by varying the task parameters like external torque, handle width, and thumb positions was performed [45]. Thumb positions significantly affected the load force of the thumb and virtual finger, while the changes in the handle width brought about much smaller effects. The findings of this experiment addressed what people do when manipulating the hand-held objects and why people prefer particular force patterns over others.

The above perturbation studies involved examining individual finger normal and tangential forces when there was a modification in the tangential moment arm of the thumb [14] or individual fingers [34]. Though there were studies that investigated the grip force sharing of the individual fingers when the moment arm of the thumb normal force was varied [24], none of the studies focused on investigating both the grip and load force distribution of all the individual fingers and thumb when there was a change in the moment arm of the thumb normal force. The current research focused on exploring both the grip and load force contribution of the individual fingers and thumb when there was a modification in the moment arm of the thumb grip force.

1.2.5 Motivation for the studies

Many research studies to date focused on investigating how the individual fingers and thumb would respond in varying the fingertip forces when there is any change or perturbation introduced to the object held in hand. Among all the fingers in the human hand, the role played by the thumb is crucial. Without the thumb, it is not possible to grasp the object properly. As mentioned earlier, the thumb is required for almost any kind of grip. There are certain objects in real life that required vertical sliding of the thumb for its meaningful operation. The objects include certain models of handheld portable radio, retractable ballpoint pens, pipette controllers, etc. One thing that was common among all these objects was that the thumb was placed over an unsteady base which involved in the fine control of the functionality of these objects.

In the portable radio, a provision for the volume or frequency control (in the form of the vertical tuner) is provided at the thumb side (refer Figure 1.5). Fine-tuning of the volume or frequency can be done by translating the thumb up or down vertically. Whereas, in certain retractable ball-point pens, the open and close mechanism of the pen is provided in the form of slider at the thumb side (refer Figure 1.6). If the slider is translated downwards by means of thumb, it results in the protrusion of the writing nib outside the nozzle, and upward translation will cause retraction of the writing nib inside the nozzle. The figures below show the step-by-step working of the objects.

By observing the working of these objects, the core idea of providing the freedom to translate the thumb vertically while grasping an object emerged. Hence, an attempt to answer how other fingertip forces re-distribute to counter-balance for the disturbance caused to the equilibrium of the handheld object has been made. This research provides the details on how the grip and load forces of individual fingers and thumb re-arrange when the base on which the thumb placed was made unsteady in the vertical direction. The involvement of the individual fingers to substitute the role of the thumb in holding the object steady has been examined closely.

		
a) Side view of the radio with two vertical sliders - the one to control the volume is found at the middle	c) Slider translated upwards to raise the volume	d) Slider translated downwards to lower the volume

Figure 1.5 Volume control of the handheld portable radio using thumb. The figure shows the handheld portable radio with the slider control towards thumb side for the fine adjustment of the volume. The step-by-step operation of the slider in the vertical direction is shown.

Thus, the thumb was perturbed by mounting it over an unsteady platform in the current research. Previously studies were involved in understanding the forces exerted by the the individual fingers when the location of the thumb was varied discretely while grasping [24], [45] and by using low-frictional material such as rayon or silk over the thumb-sensor interface [15].

a) Vertical slider initiated to move down by the thumb	b) Vertical slider translated down by the thumb, and the refill nib protrudes out to write.	c) Vertical slider retracted backward, and the refill nib goes back

Figure 1.6 Open and close mechanism of retractable ball pen. The figure shows a person holding the retractable ball point pen with a sliding mechanism on the thumb side. The step-by-step procedure for operating the slider in the vertical direction by the thumb is shown

Although there were studies performed to vary the thumb location and fingertip friction, the present study examines the role of peripheral fingers in sustaining the rotational equilibrium disturbed due to the unsteady thumb platform. Since this study involves achieving the rotational equilibrium of the handle by producing a compensatory moment, the applicability of the mechanical advantage hypothesis was examined.

As MAH is considered as one of the strategies employed by CNS in moment production tasks, it is essential to investigate if the same strategy is employed in other moment requirement tasks that was caused due to the restricted thumb contribution. Apart from this, it is also necessary to examine the underlying factor or situation that induce to employ MAH. Thus, the questions and suspicions on the strategy utilized by the system served as a motivating element for pursuing the current research. The primary objectives of the thesis have been discussed below.

1.2.6 Objectives

1. To study how the fingertip forces and moments re-distribute for establishing object stabilization when the thumb was placed on an unsteady platform.
2. To examine whether the applicability of the mechanical advantage hypothesis is task-specific and to investigate the kind of task that lend support to the hypothesis.
3. To confirm the kind of task that induces to prefer the strategy of mechanical advantage principle by restricting to produce minimal target normal force by the thumb while holding the thumb platform steady at the HOME position.
4. To investigate the biomechanical relationship between the thumb and peripheral fingers when the unsteady thumb platform was translated in the vertical direction while grasping.

CHAPTER 2.

ULNAR FINGER CONTRIBUTION WHILE GRASPING A HANDLE WITH UNSTEADY THUMB PLATFORM

2.1 INTRODUCTION

Many of our daily activities, such as holding a pen or lifting a cup, demand the use of our hands. An object held in hand must be maintained stationary, i.e., in static equilibrium, to prevent tilt and slip. Studies have used a prehension handle to examine how forces of fingers and thumb are controlled during grasping. It is known that there will be a change in the distribution of fingertip normal forces whenever there is a change in the tangential force due to vertical lifting of the object followed by expected or unexpected changes in the load of the object [46]. Also, it has been shown that there exists a tight temporal relationship between the grip and load forces during the point-to-point and cyclic arm movements with various types of grips [47]. In addition to this, the frictional state of the grasping surface was altered with different materials (like sandpaper, suede and silk) to exhibit a change in the tangential force, which would be accompanied by the scaling of normal forces [48].

Similarly, the fingertip forces get redistributed among the individual fingers and thumb due to the alteration in the direction and magnitude of the external torque imposed on the handle [49]. In a study by Aoki and colleague's friction at the object-finger interface of the thumb and fingers side was altered to examine the force distribution [15]. Tangential forces on the smoother side were lower than, the rougher side, whereas the normal forces were modulated based on the frictional condition.

Studies on prehension stability have also shown that during tasks involving the production of pronation or supination moment, fingers with larger moment arms for normal force tend to produce a greater share of normal force compared to the fingers with the shorter moment arms (i.e. middle and ring fingers). In this study, as per the handle design, the finger force sensors were placed 2 cm away from each other. Therefore, the index and little fingers have longer moment arms for normal force when the fingers are placed on the sensors. This led to the formulation of the mechanical advantage hypothesis (referred to as MAH henceforth) [31], [33]. Zatsiorsky and colleagues conducted an experiment using five-finger prehension handle with a horizontal bar fitted at the base of the handle [25]. In each trial, a specific mass was suspended on the bar at a specific distance from the center of the handle. The task was to maintain the static equilibrium of the handle by producing either pronation or supination moment. They found that the moment arm of the finger had a monotonic non-linear relationship with the force produced by that finger. The index finger exerted higher grip force than the middle finger during the pronation moment. Likewise, the little finger produced higher grip force than the ring finger during the supination moment. A similar handle was employed in the study [13], although the external torque acted in the direction perpendicular to the grasp plane in that study. The task was to hold the handle in static equilibrium by performing radial or ulnar deviation to counteract the external torque. Normal force exerted by the peripheral fingers was greater than the normal force magnitude produced by central fingers to compensate for the external torque. In both these studies, external torque was introduced by means of suspending load on the beam, and individual fingers produced compensating moments to counterbalance the external torque. Also, MAH was tested in the grasping task that involves cyclic motion of the handle in the presence of external load at different positions [32]. The hypothesis was supported in all the above studies.

One common objective of researchers 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 [14] or individual digit width other than the thumb in horizontal [34] and individual digit placement (other than the thumb in the vertical direction) [44]. In real life, 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. Proper orientation and positioning of the object are necessary for a stable grasp. The question of how object stabilization is achieved in such objects to compensate for the change in the moment caused due to the vertical unsteadiness of the thumb slider has not been examined in the literature. In the current study, a slider was positioned on the thumb side of the handle. In this way, the contribution of the thumb in holding the handle was artificially reduced. Although the current study's handle design does not closely resemble any of these objects, the core idea of providing an unsteady platform for the thumb emerged by observing the working of these objects. As a result of the reduction in the thumb contribution to hold objects, tangential force of thumb reduces. This, in turn, caused a decrease in the clockwise moment produced by the thumb. In response to this change, a counteracting supination moment has to be produced to establish handle stabilization. As a preliminary step, it is necessary to address how object stabilization is achieved during static holding (with the thumb static). As per the MAH, it was expected that the little finger would produce greater normal force in comparison to its neighboring finger to overcome the effect caused due to unsteady thumb platform. Thus, it was hypothesized that the little finger with the larger moment arm would exert greater normal force in comparison to the ring finger with the shorter moment arm when the thumb contribution was artificially reduced.

Secondly, with regard to the drop in the load contribution of the thumb, there would be an increment in the tangential force of the virtual finger (VF). Virtual finger is an imaginary finger whose output is equal to the collective summation of the mechanical output from index, middle, ring, and little fingers [16]. Since index and middle fingers are considered as independent and strong [50], it was expected that they would share greater tangential force, which should be accompanied by the increase in the grip force. However, such a rise in the normal forces of radial fingers would cause a further tilt in the counter-clockwise direction. Therefore, to avoid such tilt, the normal forces of the radial fingers should remain unchanged, resulting in the drop of safety margin of the same. Hence, it was hypothesized that the safety margin of the radial fingers would drop when the thumb platform was free to slide in comparison to the thumb platform kept fixed. Furthermore, for a clear interpretation of the sequential local changes in the individual fingertip forces, chain effects [51], [49], [30], [36] was investigated. Chain effects refer to a sequence of local cause-effect adjustments which were necessitated either mechanically or as a choice made by the controller.

2.2 MATERIALS AND METHODS

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

2.2.2 Experimental setup

A vertically oriented five finger prehension handle made of aluminium has been designed specifically for this study. The thumb side of this handle had a vertical railing. On this railing, a slider platform was placed in such a way that it can move only in the vertical direction. The slider had ball bearings, and hence the friction between the slider and the railing was minimal (μ~ 0.001 to 0.002). The handle was stored in a dust-free environment during non-use. Further, the ball bearings were regularly cleaned and lubricated between experimental sessions to ensure minimal friction. Five 6-axis force/torque sensors (Nano 17, Force resolution: 0.0125N) were used 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 could freely move in the vertical direction, whereas the other finger sensors were fixed to the handle.

A laser displacement sensor (resolution,5µm; OADM 12U6460, Baumer, India) was mounted on a flat acrylic 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 reference 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 was positioned 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 2.1. Signals from the force/torque sensors and single-channel analog laser displacement data were digitized using NI USB 6225 and 6002 (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.

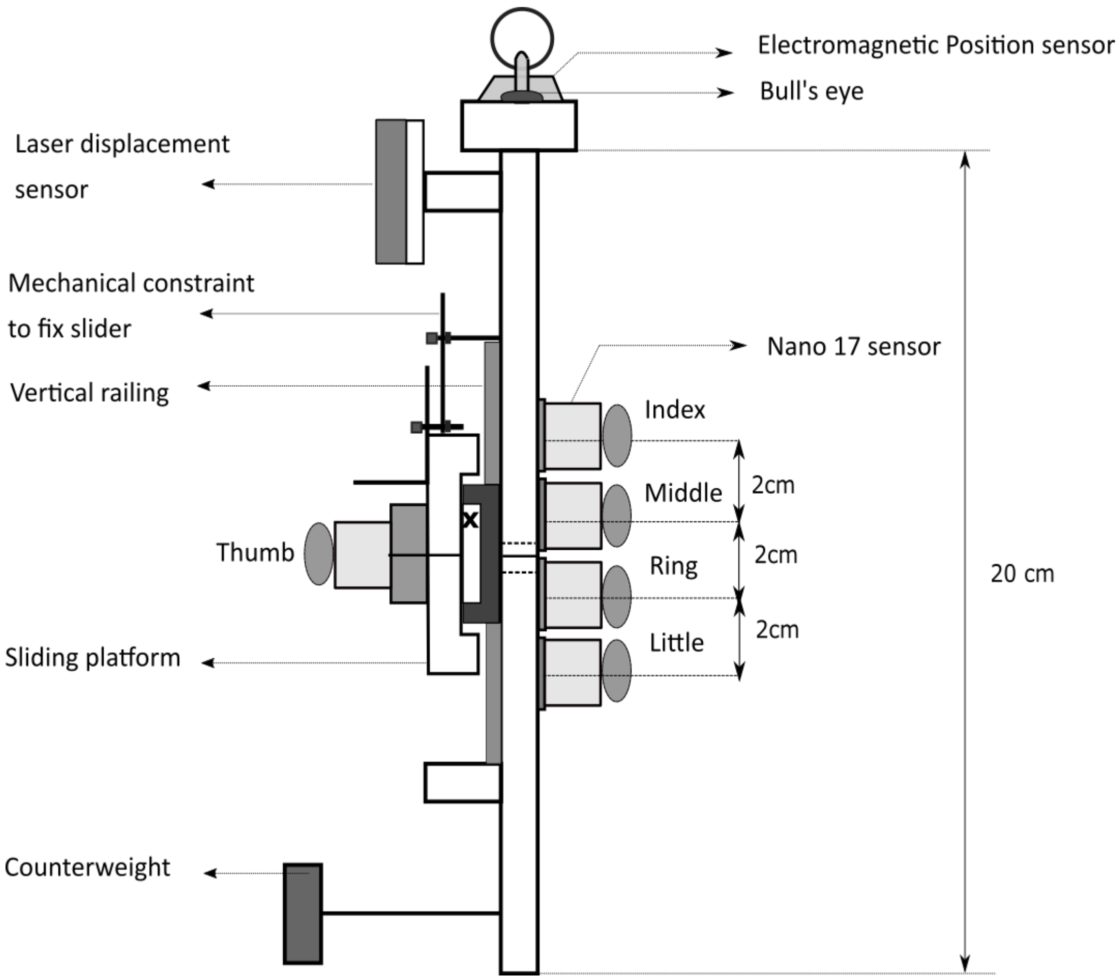

Figure 2.1 Schematic diagram of the experimental setup ATI Nano 17 force sensors mounted on the handle frame (20cmx1cmx3cm) to measure the forces of fingers (I-Index, M-Middle, R-Ring, Little-L, Th-Thumb). The geometric centre of the handle is represented by the symbol 'X' on the slider. The centres 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, the 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. The surface of all the force sensors were covered 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

2.2.3 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.

2.2.3.1 Friction experiment

A device that consists of a six-component force/torque sensor mounted on the top of the aluminium platform has been designed as shown in Figure 2.2. The platform moved linearly with the help of a timing belt-pulley system powered by a servomotor [52], [53]. A LabVIEW code 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. Normal force exerted by the instructed finger was fed as feedback on the 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. The friction coefficient was computed by dividing the tangential force and normal force at the time of slip.

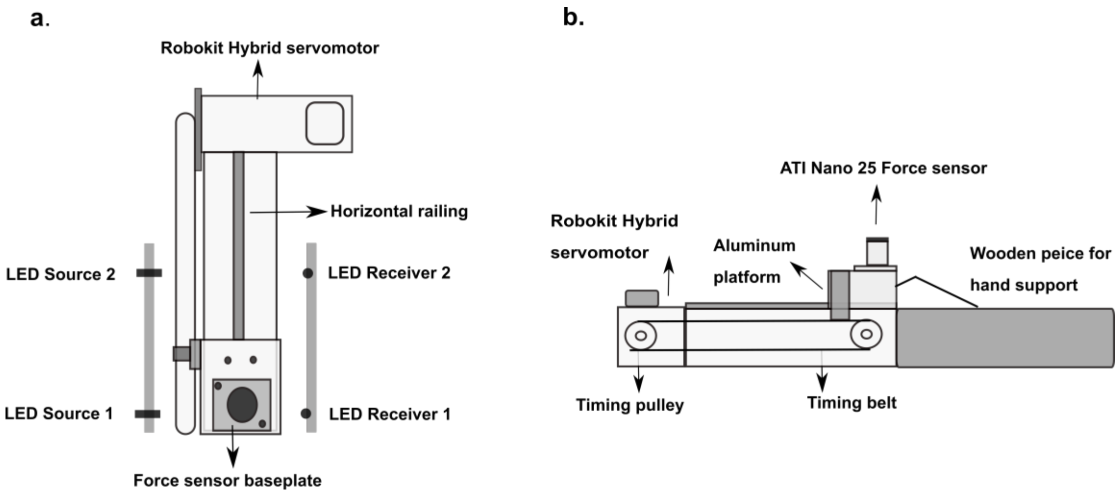

Figure 2.2 Schematic diagram of the Friction experimental apparatus a. Top view of the friction setup with LED source and receiver to detect the position of the thumb slider platform on the linear horizontal railing. b. Side view of the friction setup showing force sensor, timing pulleys and belt

2.2.3.2 Prehension experiment

Participants were seated comfortably on a wooden chair with their forearm resting on the table, as shown in Figure 2.3. 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. The natural grasping position can be achieved by supinating the forearm at 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 fixed securely using a mechanical constraint. This fixed position was such that the horizontal line drawn at the mid of the thumb platform was precisely matched with the solid horizontal line drawn at the mid of the handle (i.e., midway between middle and ring finger sensors). In the free condition, this mechanical constraint was released so 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 peripheral fingers. However, in the current study, the thumb platform has to be maintained between middle and ring fingers. This was in addition to the requirement to maintain the handle at static equilibrium. The spirit level (or bull's eye) provided tilt feedback to the participant.

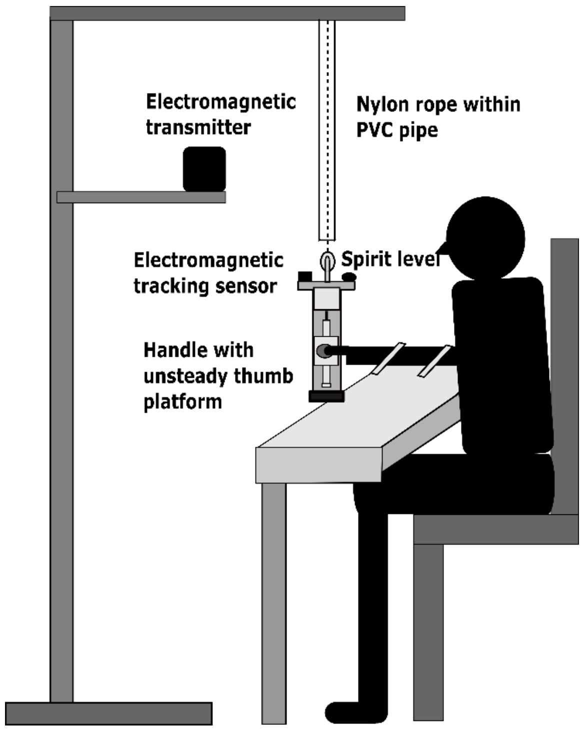

Figure 2.3 Schematic diagram of the participant holding the handle Thumb side of the handle is shown. The entire handle setup was suspended from a wooden frame using nylon rope passing through a hollow PVC pipe. The PVC pipe allowed slight movement of the rope (and handle) but not undesirable large amplitude 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 a few cm away from the handle to avoid distortion.

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 hold the handle vertical by maintaining the bubble in the bull's eye at 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 at the midline between the central fingers in the free condition. Although the friction between the thumb platform and handle was low, it was not zero. The experimental task required some practice. Five practice trials were provided at the start of each condition (not analyzed). After practice, participants were able to follow the instruction and perform the task successfully. Each experimental condition was conducted in a separate session. A break of one hour was provided between conditions. In each condition, thirty trials were recorded. Each trial lasted for ten seconds, with a minimum mandatory rest of 30s between the trials. Based on the participants request, additional rest was provided.

2.3 Data Analysis

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

2.3.1 Normal force sharing (%)

Grip force shared by the individual fingers (excluding the thumb) was expressed in terms of percentage by taking the average across 500 samples of each trial and then averaged across all trials and participants.

2.3.2 Percentage change in normal and tangential force

Although some participants performed the "free" condition first, since the fixed condition was considered as control, % change was computed 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.

$$\%\ \text{Change in Normal force (NF)} = \frac{(\text{Average NF in free condition} - \text{Average NF in fixed condition})}{\text{Average NF in the fixed condition}} * 100 \quad (2.1)$$

Likewise, % Change in tangential force was also computed.

2.3.3 Safety margin

Safety margin (SM) is the amount of extra grip force applied in addition to the minimally required grip force to prevent slipping of the handle. It was computed for all fingers using the following equation [28], [51], [54].

$$SM(t) = \frac{\left[F_n - \frac{|F_t|}{\mu}\right]}{F_n} \tag{2.2}$$

where μ is the coefficient of friction between the finger pad and sandpaper, t refers to the time course of 5 seconds, F_n is the grip force, and F_t is the load 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 were 0.9689±0.0054 and 0.9745±0.0109, respectively. For statistical analysis, Fisher's Z-transformed SM (SM_z) values were found by using the following equation.

$$SM_z = 0.5 * ln\left(\frac{1+SM}{1-SM}\right) \tag{2.3}$$

2.3.4 Moment computation

For an object in static equilibrium, the moments due to the grip and load forces of individual fingers and thumb was computed as described in the previous studies [30]. Moment due to normal force of all fingers was calculated by,

$$\mathrm{M}_{\mathrm{n}}^{\mathrm{j}} = \left(\mathrm{d}^{\mathrm{j}} + \mathrm{COP}_{\mathrm{y}}^{\mathrm{j}}\right)\mathrm{F}_{\mathrm{n}}^{\mathrm{j}} \tag{2.4}$$

$$COP_y = \frac{M_x}{F_n} \tag{2.5}$$

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

$$M_n^I + M_n^M + M_n^R + M_n^L = M_n^{VF} \tag{2.6}$$

Moment due to thumb tangential force,

$$M_t^{Th} = -r^{Th} F_t^{Th} \tag{2.7}$$

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

$$M_t^I + M_t^M + M_t^R + M_t^L = M_t^{VF} \tag{2.8}$$

$$M_n^{VF} + M_t^{VF} = \text{Total Moment } (M_{tot}^{VF}) \tag{2.9}$$

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 [15], [30]. 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.

2.3.5 Synergy analysis

Finger force covariation was quantified to examine the existence of synergy. The term "synergy" is defined as "a neural organization of a set of elemental variables with the purpose of stabilizing a certain performance variable" [55]. As in the previous studies [55], [51], [56]–[58], synergy analysis on the mechanical variables was performed at two different levels: Virtual Finger-Thumb (VFTH) level and the Virtual finger (VF) level.

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 indicate 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 standard error of the mean (SEM) was found.

Synergy index was calculated by using the below equation.

$$\Delta V = \frac{\sum Var(EVs) - Var(PV)}{\sum Var(EVs)} \tag{2.10}$$

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 the mean was found. Fisher Z transformation was performed to the ΔV values of each participant for statistical analysis by using the following equation.

$$\Delta V_z = 0.5 * ln\left(\frac{1+\Delta V}{1-\Delta V}\right) \tag{2.11}$$

Synergy index was calculated for the following performance variables found on the left-hand side of the below equations [57].

At VFTH level:

$$\mathrm{F_n^{VFTH}} = \mathrm{F_n^{VF}} + \mathrm{F_n^{Th}} \tag{2.12}$$

$$\mathrm{F_t^{VFTH}} = \mathrm{F_t^{VF}} + \mathrm{F_t^{Th}} \tag{2.13}$$

$$\mathrm{M_{tot}^{VFTH}} = \mathrm{M_n^{VF}} + \mathrm{M_t^{Th}} + \mathrm{M_t^{VF}} + \mathrm{M_n^{Th}} \tag{2.14}$$

At VF level:

$$\mathrm{F_n^{VF}} = \mathrm{F_n^{I}} + \mathrm{F_n^{M}} + \mathrm{F_n^{R}} + \mathrm{F_n^{L}} \tag{2.15}$$

$$\mathrm{F_t^{VF}} = \mathrm{F_t^{I}} + \mathrm{F_t^{M}} + \mathrm{F_t^{R}} + \mathrm{F_t^{L}} \tag{2.16}$$

$$M_n^{VF} = M_n^{I} + M_n^{M} + M_n^{R} + M_n^{L} \tag{2.17}$$

$$M_{tot}^{VF} = M_n^{VF} + M_t^{VF} \tag{2.18}$$

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

2.3.6 Linear discriminant analysis

To examine how the change in tangential force of the thumb affect the moment due to normal forces of other fingers and the static equilibrium of the object, Linear Discriminant Analysis (LDA) was performed. 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} & $(M_n^{R} + M_n^{L})$.

A linear discriminant classifier was trained with the set of data points on thumb tangential force and the moments mentioned above for the two conditions. LDA was performed for the four pairs of variables mentioned above.

2.3.7 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 pairwise comparisons were performed using Tukey test to explore the significance within the factors. Equivalence test using Two One-Sided T-test (TOST) approach [59] was performed to check for equivalence of the tilt angles and safety margin between fixed and free conditions. Furthermore, the equivalence test (TOST) was performed (both for absolute and % values) between the grip forces of the ring and little fingers during the free condition to check if they are comparable. The TOST test approach on the six comparisons (tilt angles, safety margin of index, middle, little fingers, normal forces of ulnar fingers, % of normal force share of the ulnar fingers) were performed with the desired statistical power of 95% having a sample size of 15.

2.4 Results

The 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 2.4 (left and the right column) shows the time profiles of average normal force and average tangential force in the fixed and free conditions. Note that the mean (1.65N) and standard error of the mean (0.15N) of Index finger normal force during free condition found to be greater than the mean (1.63N) and standard error of the mean (0.11N) of Index finger normal force during the fixed condition. Since the index finger normal force data (both mean and standard error) during fixed condition was found lower than the free condition, fixed condition data was found hidden below the free condition data when they were plotted. Similarly, the grey-shaded portion of the index and middle finger tangential force in free condition (i.e. standard error) hides the dashed line plot of the index and middle tangential force in the fixed condition at the midway.

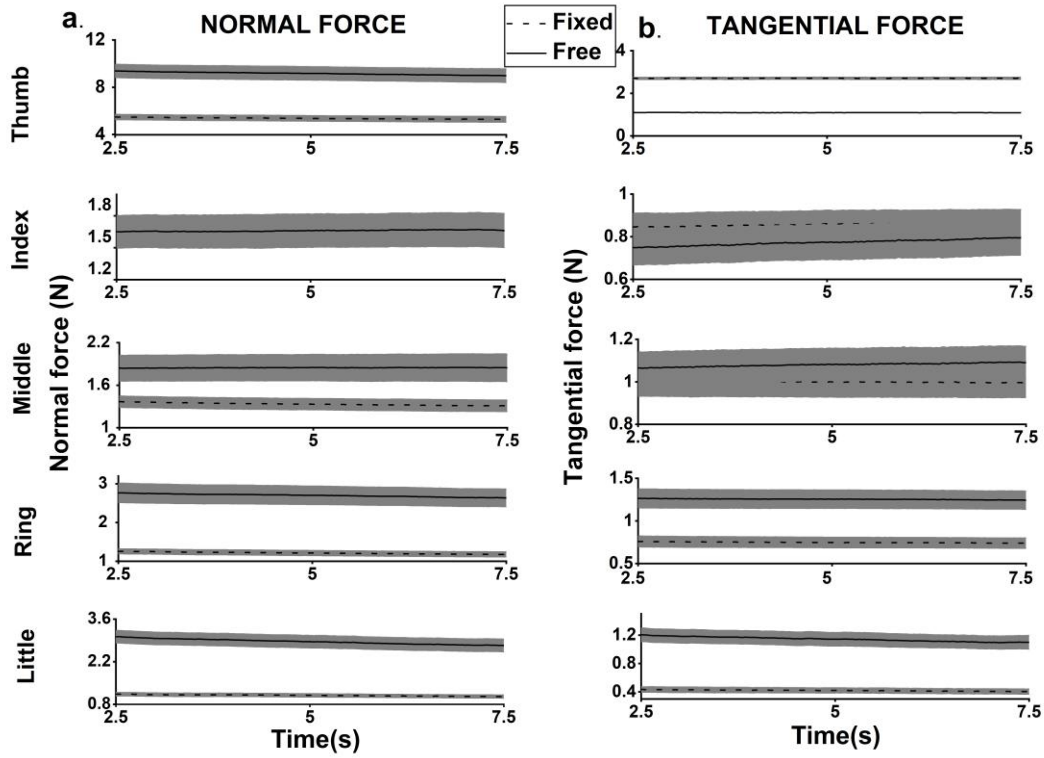

Figure 2.4 a. Average time profile of Normal force b. Average time profile of Tangential force of all the fingers during fixed and free conditions Data shown are averages across subjects & trials in each condition. Fixed condition is represented with dashed lines and free condition represented with solid line. Thick lines and shaded areas refer to the means and standard error of means.

The tilt angles showed no statistically significant difference (fixed condition: Mean=4.13º, SD=2.31; free condition: Mean=3.83º, SD=1.82, $t(28)=0.395$, $p=0.696$, d=0.14). The TOST procedure for the independent tilt angle samples was performed with the smallest effect size of interest (SESOI=1.31) set as equivalence bounds (lower limit Δ_L= -1.31 and upper limit Δ_U=1.31) obtained for the desired level of statistical power of 95%. The procedure revealed that the comparison was statistically equivalent ($t(28) = -3.192$, $p = 0.00174$) as the observed effect size (d) falls within the equivalence bounds. The amount of divergence of the center of the thumb sensor from the marked position on the handle frame was calculated. It was computed by finding the absolute difference between the maximum and minimum values of the laser displacement data within each trial. This difference was then calculated for all trials, averaged, and then averaged across participants. During the free condition, the average divergence of the marked horizontal line on the slider from the horizontal line on the handle was 0.88±0.06 mm.

2.4.1 Grip and load forces of the fingers and thumb

The average grip force of the middle, ring, little fingers, and the thumb in free condition was statistically higher than that in the fixed condition. The average thumb tangential force in the free condition decreased significantly compared to the fixed condition. This decrease in the thumb's load force was compensated by the increase in the load force and grip force of the ring and the little fingers to maintain the handle at static equilibrium during the free condition. It was found that the grip force of the little finger was not statistically different from the grip force of the ring finger in the free condition (Ring finger: Mean=2.69N, SD=0.84; Little finger: Mean=2.86N, SD=0.71, $t(14)= -0.543$, $p = 0.596$, d_z=0.14). By employing the TOST procedure with equivalence bounds of Δ_L= -0.93 and Δ_U= 0.93 for a desired statistical power of 95%, dependent samples of normal forces of the ulnar fingers were found to be statistically equivalent ($t(14) = 3.059$, $p = 0.00425$). As the observed effect size(d_z=0.14) falls within the equivalence bounds, this comparison was deemed to be equivalent.

This was true in both the absolute and % values of the normal forces. The averages (across time, trials, and participants) of normal force and tangential force can be seen in Figures 2.5(a) and 2.5(b).

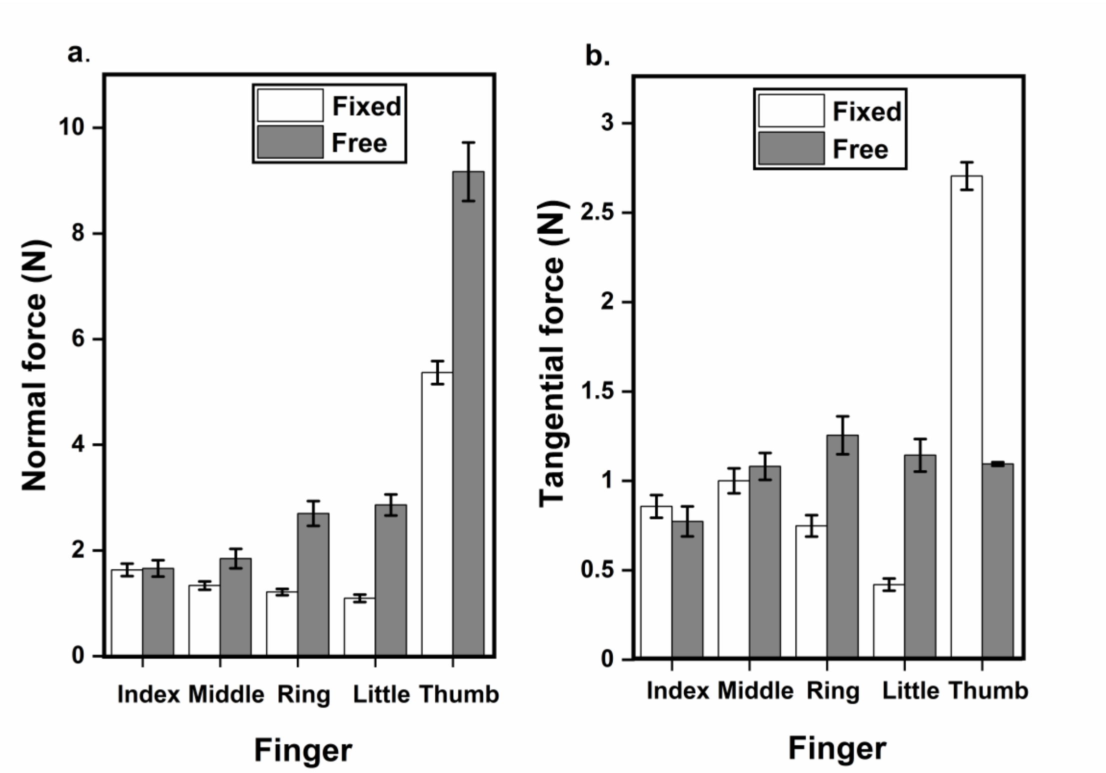

Figure 2.5 Average of Normal Force and Tangential force of all fingers at different conditions with standard error of means a. Average Normal force of Index, Middle, Ring, Little and Thumb in fixed and free condition. Normal force of middle, ring, little and thumb fingers in free condition significantly 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.

A two-way repeated-measures ANOVA on average normal force with factors condition and finger showed a statistical 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, one-way ANOVA was performed. However, there was not any such difference in the 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 grip force of the small finger (2.86N) in the free condition was significantly greater than the normal force of the index (1.63N, $p<0.01$), middle (1.33N, $p<0.001$), ring (1.21N, $p<0.001$) fingers in fixed condition and index finger (1.65N, $p<0.05$) in the free condition. Ring finger normal (2.69N) in the free condition was significantly greater than the normal force of the index (1.63N, $p<0.05$), middle (1.33N, $p<0.01$), ring (1.21N, $p<0.001$), and little (1.09N, $p<0.001$) fingers in the fixed condition.

The effects of condition on average tangential force were significant ($F_{(0.91,12.74)}=13.44; p<0.01$, $\eta^2_p=0.5$) with respect to 2-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 small finger increased significantly ($p<0.001$) in the 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). The average thumb tangential force in fixed condition (2.70N) was statistically greater ($p < 0.001$) than the average tangential force of index (0.85N, 0.77N), middle (1N, 1.08N), ring (0.74N, 1.25N), and little finger (0.41N, 1.14N) in fixed and free conditions. The average tangential force of little finger in fixed condition (0.41N) significantly decreased than the ring (1.25N, $p<0.001$) and thumb (1.09N, $p<0.001$) in free condition, index (0.85N, $p < 0.01$;0.77N, $p< 0.05$) and middle finger (1N, $p<0.001$; 1.08N, $p<0.001$) in both conditions. Ring finger tangential force in free condition (1.25N) was significantly greater than the index finger (0.85N, $p<0.01$; 0.77N, $p<0.001$) in both conditions. In the free condition, the tangential force of the little finger (1.14N) was statistically greater ($p<0.01$) than the tangential force of the ring finger in the fixed condition (0.74N). Thumb tangential force in the free condition (1.09N) was statistically greater ($p<0.05$) than the ring finger in the fixed condition (0.74N).

The pairwise comparison confirmed that the tangential force of the ring finger (0.74N) during the fixed condition was statistically ($p< 0.05$) greater than the tangential force of the little finger (0.41N) during the same condition as shown in Figure 2.5(B). Whereas, during the free condition, ring finger tangential force (1.25N) was not statistically different ($t(14) = 0.789$, $p = 0.443$) from the little finger tangential finger (1.14N). Therefore, an equivalence test was performed to check whether the ulnar fingers have exerted comparable tangential forces during the free condition. The TOST procedure confirmed that the comparison was statistically equivalent (t(14) = -2.813, p=0.00691), as the observed effect size (dz=0.36) of the dependent means was within the equivalence bounds of Δ_L = -0.93 and Δ_U = 0.93.

2.4.2 Force sharing of the normal forces

Normal force sharing was different between the two conditions. It was observed that a statistical 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. 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 2.6)**.** Further, % of normal force shared by the ring finger was not statistically different from % of normal force shared by the little finger during the free condition (Ring finger: Mean=30.97%, SD=8.25; Little finger: Mean=33.35%, SD=7.20, t(14)= -0.655, p = 0.523, d_z=0.16). However, the TOST procedure confirmed that the comparison was statistically equivalent (t(14) = 2.947, p = 0.0053), as the observed effect size was statistically within the equivalence bounds of Δ_L= -0.93 and Δ_U=0.93.

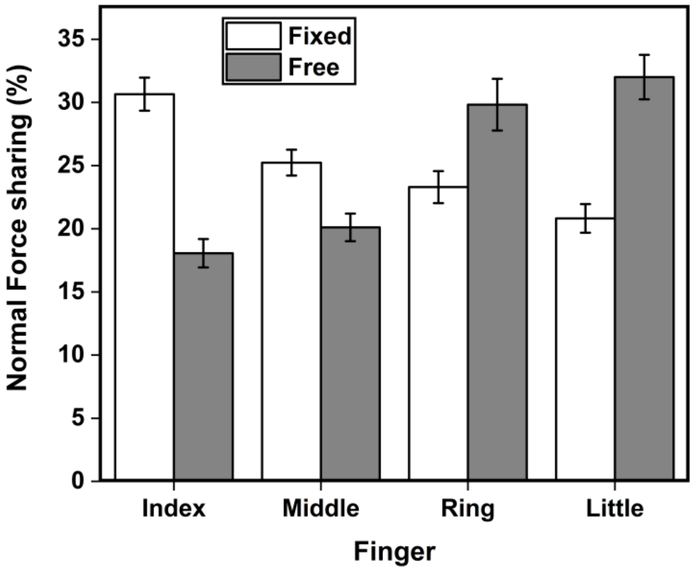

Figure 2.6 Normal force sharing in % Normal force share of the individual fingers apart from thumb for the fixed (white) and free (grey) condition is expressed in the form of percentage. In the free condition, normal force share of the ring ($p<0.05$) and little ($p<0.001$) finger significantly increased 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.

2.4.3 Percentage change in the grip and load forces

There was a drop of 60% in the load force of the thumb. This drop was compensated by 70% and 199% rise in the tangential force of the ulnar fingers in free condition with respect to fixed condition. In addition, there was a simultaneous rise in the grip 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 2.7).

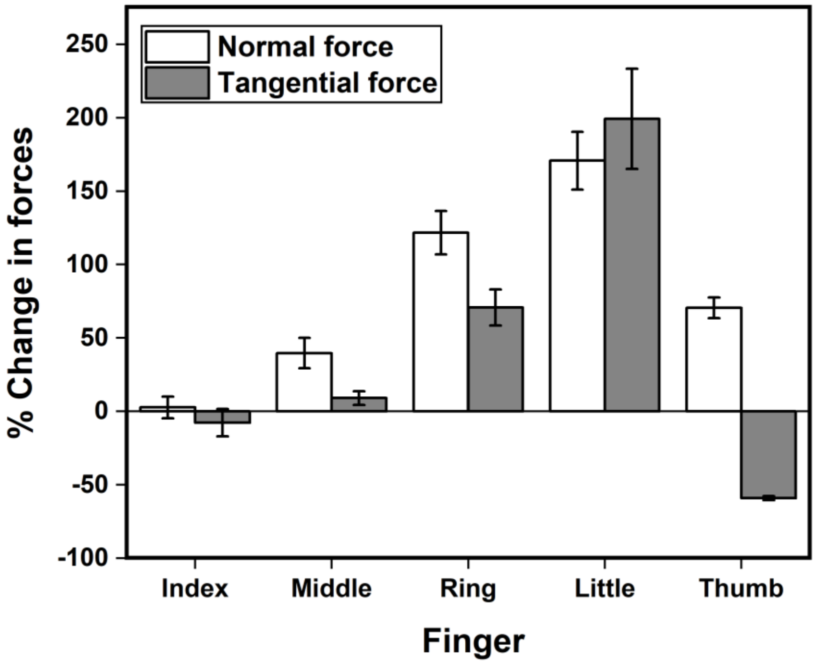

Figure 2.7 Percentage change in the Normal and Tangential forces Normal force is represented in white and the Tangential force is represented in grey. All changes are computed for the free condition compared to the fixed condition. Normal force of the middle, ring, little and thumb increased by 40%, 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%.

2.4.4 Safety Margin of the individual fingers and thumb

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 finger ($F_{(3.44,48.16)}=29.26$;$p<0.001$, $\eta^2_p=0.67$) showed statistical significance. Post-hoc pairwise comparisons showed significantly higher SM_z for ring finger ($p<0.05$) and thumb ($p<0.001$) in the free condition when compared to fixed condition as shown in Figure 2.8. Interaction effect also showed statistically significant difference ($F_{(3.56,49.84)}$=66.11;p<0.001, η^2_p =0.82) for the safety margin between the factors.

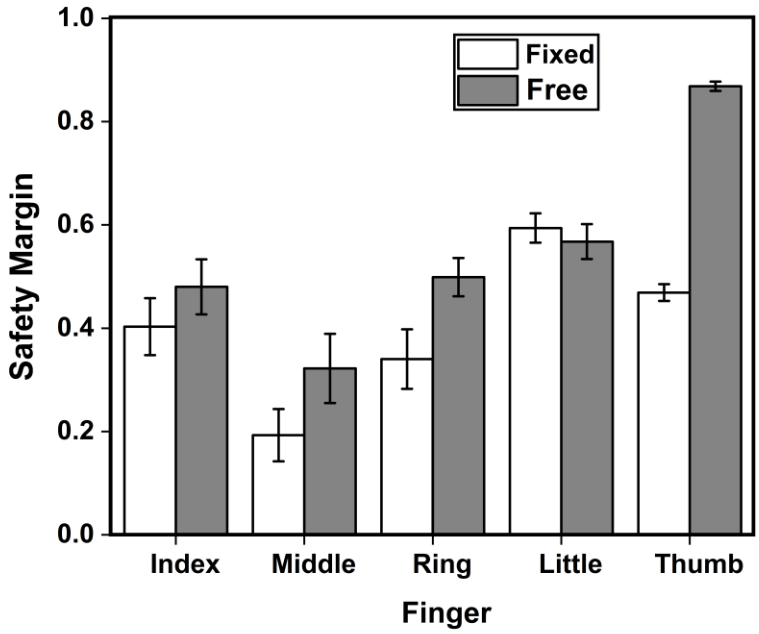

Figure 2.8 Safety Margin of individual fingers and thumb in fixed and free conditions Safety margin of thumb (p<0.001) and ring (p<0.05) finger in the free condition significantly increased compared to the fixed condition. Safety margin of the index, middle and little fingers in free condition were found to be equivalent to the safety margin of the corresponding fingers in the free condition.

During the fixed condition, the safety margin of the little finger (0.70) was significantly (p<0.01) greater than the ring finger (0.37). However, during the free condition, the safety margin of the ulnar fingers (Ring finger: Mean = 0.56, SD = 0.18; Little finger: Mean = 0.66, SD = 0.20, t(14) = -1.425, p=0.176, dz=0.36) were not statistically different. Therefore, statistical equivalence was tested. By employing the TOST procedure, with equivalence bounds of Δ_L = -0.93 and Δ_U = 0.93, for a desired statistical power of 95%, dependent samples of safety margin of the ulnar fingers were found to be statistically equivalent ($t(14)=2.17$, $p=0.02$). As the observed effect size($dz=0.36$) falls within the equivalence bounds, this comparison was deemed to be equivalent.

The safety margin of the thumb in the free condition (1.34) was significantly greater ($p<0.001$) than the safety margin of the index (0.45, 0.55), middle (0.20, 0.35), ring (0.37, 0.56) and little (0.70, 0.66) in fixed and free conditions. Middle finger safety margin during free condition (0.35) was significantly ($p<0.01$) lower than the little (0.70, 0.66) in both conditions. In fixed condition, middle finger safety margin (0.20) decreased significantly compared to the little finger (0.70, $p<0.001$; 0.66, $p<0.001$) in both conditions, index (0.45, $p<0.01$) and ring (0.37, $p<0.001$) in the free condition, thumb (0.51, $p<0.01$) in the fixed condition.

In addition to this, the safety margin of index finger (Mean=0.45, SD=0.26) in fixed condition was not statistically different ($t(28)= -1.031$, $p =0.311$, $d=0.37$) from safety margin of index finger (Mean=0.55, SD=0.25) in free condition. Similarly, the safety margin of middle (Mean=0.20, SD=0.19) and little fingers (Mean=0.70, SD=0.19) in fixed condition was not significantly different (Middle: $t(28)= -1.796$, $p =0.0833$, $d=0.64$; Little finger: $t(28)= 0.582$, $p =0.565$, $d=0.20$) from safety margin of middle (Mean=0.35,SD=0.28) and little finger (Mean=0.66, SD=0.19) in free condition. A statistical equivalence was observed among the safety margin of index ($t(28) = 2.557$, $p = 0.00814$), middle ($t(28) = 1.792$, $p = 0.042$) and little fingers ($t(28) = -3.005$, $p = 0.00277$) between the fixed and free condition as their observed effect sizes falls within the equivalence bounds of $\Delta_L= -1.31$ and $\Delta_U=1.31$. It was confirmed through TOST T-test. These findings are illustrated in Figure 2.8.

2.4.5 Moments

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 Figure 2.9). The increase in the moment due to normal force of virtual finger in free condition was mainly due to the rise in the grip force of middle, ulnar fingers, not index finger.

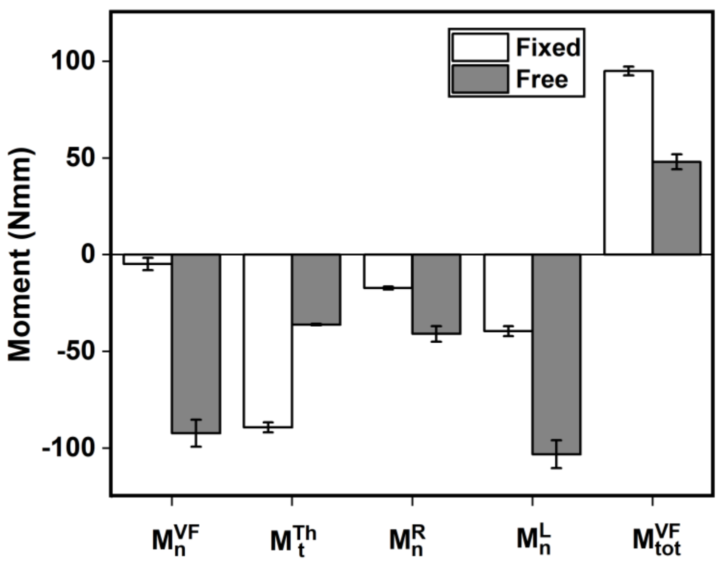

Figure 2.9 Average moment during fixed and free condition Moment due to normal force of Virtual finger (M_n^{VF}), Moment due to tangential force of thumb (M_t^{Th}), Moment due to normal force of ring finger (M_n^R), Moment due to normal force of little finger (M_n^L) and Total moment due to Virtual 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 the 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 the virtual finger, approximately

compensating for the decreased clockwise moment due to the normal force of the thumb. The columns and error bars indicate means and standard error of means

Pairwise post-hoc Tukey tests was performed 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. In addition to this, pairwise post-hoc comparisons also showed a statistically significant drop ($p<0.001$) 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).

2.4.6 Synergy analysis

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 Figure 2.10). Note that the ΔV indices at VF level were positive for tangential force and total moment (M_{tot}) in both conditions. Figure 2.10 presents actual ΔV values, whereas statistical analysis was performed with Z-transformed ΔV values.

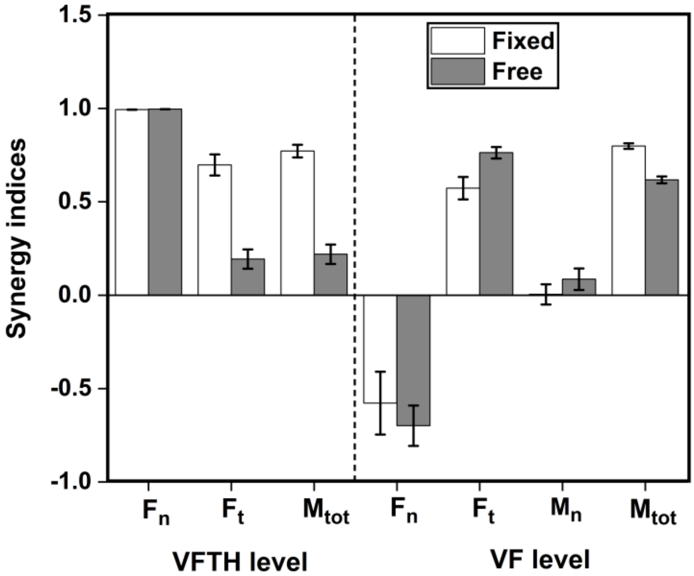

Figure 2.10 Synergy indices (ΔV) for different performance variables at VFTH and VF level Synergy index for the performance variables at VFTH level: Normal force (Fn), Tangential force (Ft), and Total moment (Mtot) are shown on the left side of the vertical dashed line. Synergy index for the performance variables at VF level: Normal force (Fn), Tangential force (Ft), Moment due to normal force (Mn) and Total moment (Mtot) are shown on the 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 the 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.

2.4.7 Classification accuracy

The change in the moment caused by the normal force of the individual fingers due to the change in the tangential force of the thumb during the fixed and free conditions was investigated using linear discriminant analysis (LDA). 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 grip forces of the individual fingers. LDA was able to predict the test data at an accuracy of 98%, sensitivity of 100%, specificity and precision of 97%, false-positive rate of 2% for all four cases. This result is illustrated in Figure 2.11. The results for the other pairs of variables are included in Figure 2.12, Figure 2.13 and Figure 2.14.

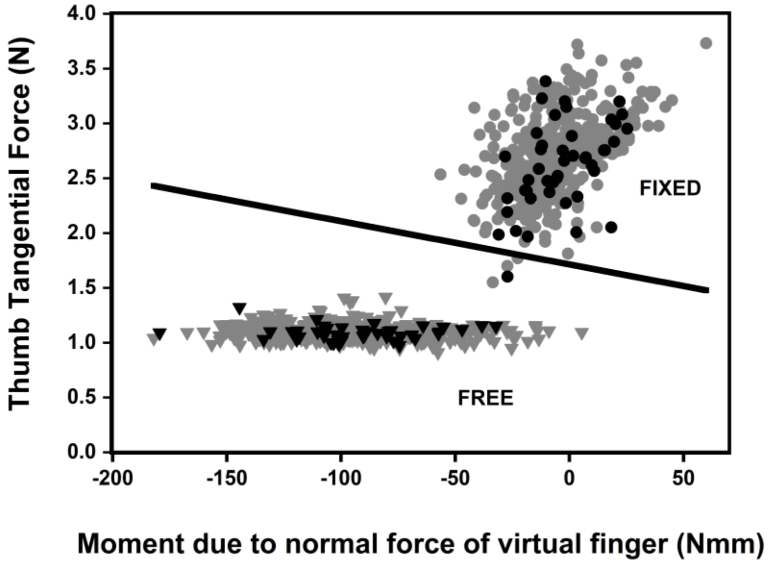

Figure 2.11 Thumb tangential force (F_t^{Th}) as a function of Moment due to normal force of Virtual Finger (M_n^{VF}) Each datapoint in the scatter plot represents time average of a single trial of a single subject. Data from all subjects are presented. Inverted triangle in grey & black colours are 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%.

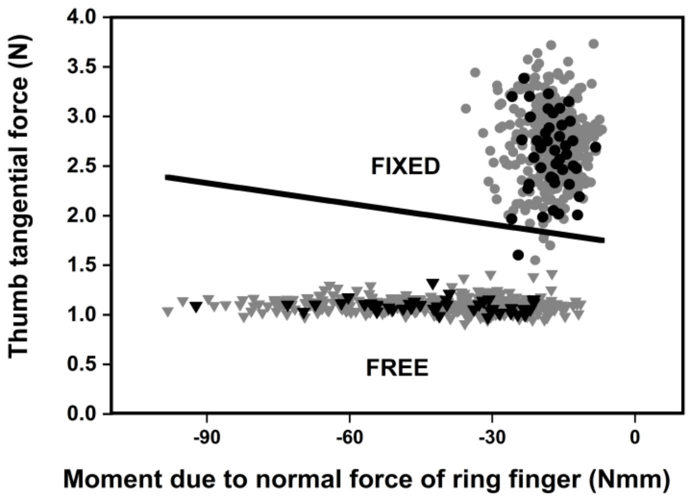

Figure 2.12 Thumb load force (LF-TH) as a function of moment due to the normal force of ring finger (Mn-R). Each datapoint in the scatter plot represents time average of a single trial of a single subject. Data from all subjects are presented. Inverted triangle in grey & black colours are train (405) 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

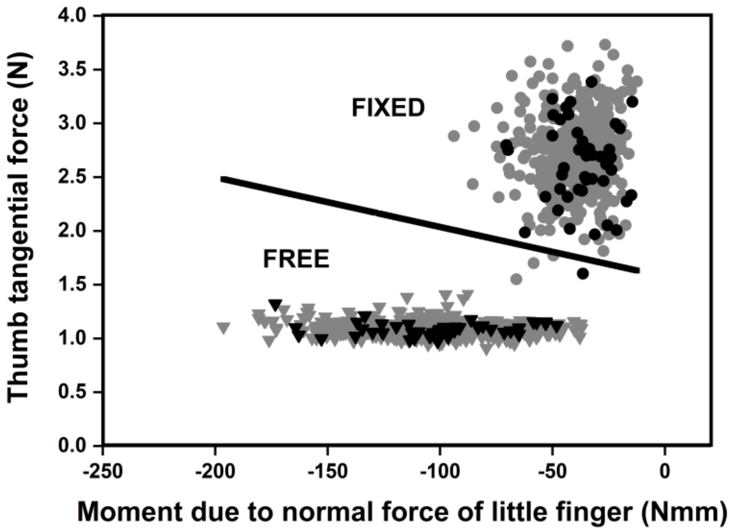

Figure 2.13 Thumb load force (LF-TH) as a function of Moment due to the normal force of little finger (Mn-L). Each datapoint in the scatter plot represents time average of a single trial of a single subject. Data from all subjects are

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.

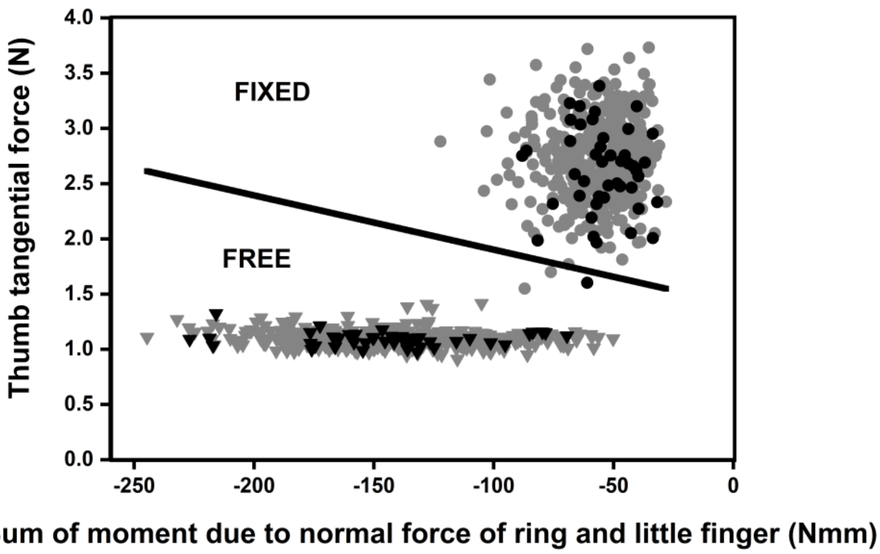

Figure 2.14 Thumb load force (LF-TH) as a function of sum of the Moment due to normal force of ring and little finger (Mn-RL). Each datapoint in the scatter plot represents time average of a single trial of a single subject. Data from all subjects are presented. Inverted triangle in grey & black colours 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.

2.5 Discussion

In the current study, participants attempted to maintain the handle at 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 on the surface between the thumb platform and handle can be perceived by the proprioceptors 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 critical difference between conditions is that in the “free condition” the thumb cannot apply the desired vertical tangential force as found in the fixed condition. The tangential force of the thumb dropped from ~ 2.7N to 1N during the free condition. The thumb could only produce 1N force without causing a translation of the slider. If the participant attempts to increase the tangential force above 1N, the thumb platform will slide upwards (violation of experimental instruction).

The drop in the thumb’s 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 will disturb the rotational equilibrium of the handle. Eventually, there was a compensatory adjustment in the fingertip forces to retain the equilibrium of the handle. 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 were introduced to the handle. From their results [34], [57], it was found that the peripheral fingers exert greater normal force. In this 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's tangential force could cause a tilt of the handle in the counter-clockwise direction. In order to overcome such tilt, clockwise moment (or supination moment) has to be produced by the grip force of the ulnar fingers. Hence, the little finger was expected to produce grip force than the ring finger, causing clockwise moment in-order to bring the handle back to its equilibrium state.

However, both the ulnar fingers exerted a statistically equal absolute normal force (in Newton) and normal force sharing (in terms of %). Thus, results are not supporting 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 [13], [32], which found support for the mechanical advantage hypothesis. Further, in other studies [25], external torques imposed on the handle was in the range of Newton-meter (Nm). In this study, counter-clockwise tilt caused due to the drop in the thumb's tangential force was in the range of Newton-centimeter (Ncm), which is comparatively lesser. Also, not all the results of a study on the coordination of fingertip forcea during the moment production on a object that was fixed mechanically [29] supported the mechanical advantage hypothesis. One similarity between the present study and torque production study on a object that was fixed mechanically [29] was that the task involved moment production by the fingers (other than the thumb). However, in this study, changes in thumb forces are not due to the external torque introduced to the handle but rather due to the artificial ("forced") reduction in the thumb contribution to hold the handle. Further research is needed with different conditions to check whether there is a monotonic relationship between the finger moment arm and force during various conditions in such tasks involving an artificial reduction in thumb contribution.

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 2.15). Consequently, thumb's normal force increased to 9N (almost doubled compared to thumb's 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 [54]. The normal force of the thumb increased in a "feed-forward" manner. A 'non-slip strategy' [41] for the thumb by raising the safety margin of the thumb (see Figure 2.8) 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 Figure 2.9). Further, the shift in center of pressure (COP) of the fingers and thumb in the vertical direction to compensate for the tangential force drop in the thumb was examined. A planned pairwise comparison on the difference in COP shift from the initial to the final point between the conditions was performed. There was not any significant difference in all the fingers and thumb.

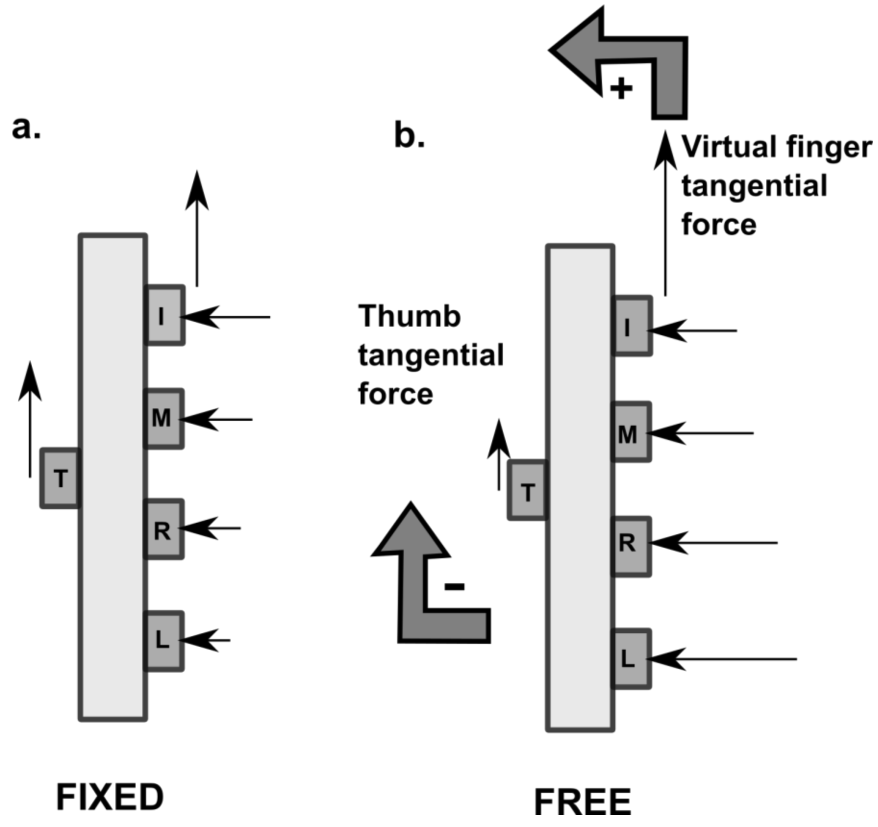

Figure 2.15 Force and Moment distribution pattern in fixed and free condition The length of the arrow corresponds to the absolute magnitude of the force. In fixed condition, moment due normal force of virtual finger (M_n^{VF}) is approximately zero and moment due to normal force of thumb (M_n^{Th}) is 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

From the results of this study, it was observed that a significant increase in the safety margin of the ulnar finger as there was a rise in the grip force of the ulnar finger to compensate for the drop in the load force of the thumb. It is known that the tangential force of the virtual finger increases to compensate for the drop in the load force of the thumb in order to maintain the handle at static equilibrium. Prior studies [11], [21], [60], [61] have shown that the index and middle fingers play a major role in producing greater forces compared to the ulnar finger. Next to the thumb, the index finger is considered to contribute in a great way for the independent force control [62]. Meanwhile, the middle finger (one among the central finger) was responsible for supporting the weight of the handle [25]. Therefore, the speculation was that the index and middle finger would share a greater tangential force compared to the ring and small finger during the multi-finger prehension task (see Figure 2.16). However, it cannot be accompanied by the greater share of normal forces as it could cause a further tilt in the counter-clockwise direction. Hence, the expectation was that there would be a drop in the normal force of the index and middle finger in the free condition. According to the second hypothesis, there will be a significant drop in the safety margin of the index and middle finger during the free condition compared to the fixed condition. Contrary to the expectations, the safety margin of the index and middle finger showed no statistical difference between the fixed and free conditions. Hence, the findings were not in agreement with the second hypothesis as well.

One question that arises here is whether it is applicable to define the safety margin since the slider was frictionless. By definition, the safety margin does not exist when friction is zero. Friction was minimal (non-zero) between the slider and the handle due to the presence of ball bearings. Friction was much higher between the thumb and the ATI Nanosensor (~0.97, consistent with other studies). If any slip happens, it would first happen at the interface of the slider and the railing, not the sensor and finger. The instruction was to hold the thumb platform in position by matching the horizontal line on the thumb platform to the horizontal line drawn at the midline between the middle and ring finger. The participants followed the instruction without causing any vertical sliding of the thumb platform. Therefore, the safety margin of the thumb is defined and increased in the free condition.

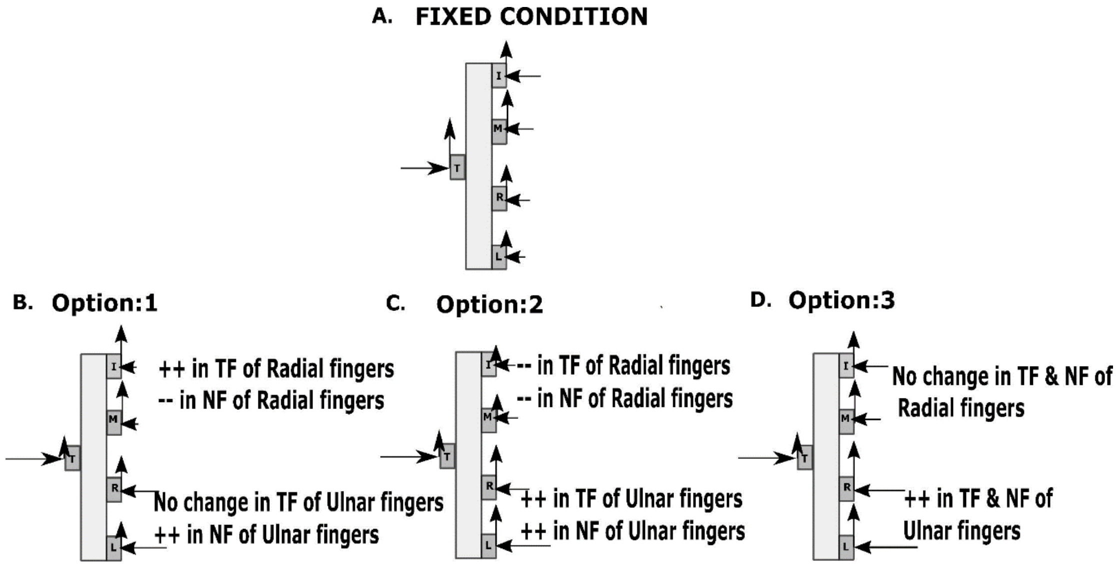

Figure 2.16 Different possibilities of changes during free condition Three different possibilities that were expected when there was a change in the force of the thumb due to the artificial reduction of thumb contribution to hold object. NF refers to Normal force and TF refers to Tangential force. Sign '++' refers to increase, and '- -'refers to decrease.

Furthermore, with regard to the equation (2.2), the safety margin depends on the fingertip forces, and the friction coefficient. Having comparable normal forces and the same friction coefficient by ulnar fingers, the next question would be to examine how the tangential force of these fingers varied? Whether it would be statistically equivalent or different? Suppose, if the ulnar fingers tangential forces were comparable, then the safety margin would also be comparable. In contrast, if the tangential forces were different, then the safety margin would also be different.

As mentioned earlier, CNS has employed the strategy of increasing tangential forces of the ulnar fingers as there was a necessity to increase the normal forces of the same to counterbalance for the reduction in the thumb tangential force. Among the ulnar fingers, tangential force sharing within ulnar fingers became a critical part. The magnitude of the force shared within the ulnar fingers might be comparable (Option 1), or the ring finger might share greater force than the little (Option 2), or the little finger might exert greater tangential force than the ring (Option 3) (see Figure 2.17). From the literature, it is found that the ring finger is stronger than the small finger from the normal strength assessing tasks[17], [26]. In addition to this, from the results of the current study, during the fixed conditions, it was observed that the ring finger tangential force was greater than the little finger tangential force. Therefore, it was expected that the CNS would choose the second option of sharing greater tangential force by ring finger than the small finger during the "free" condition.

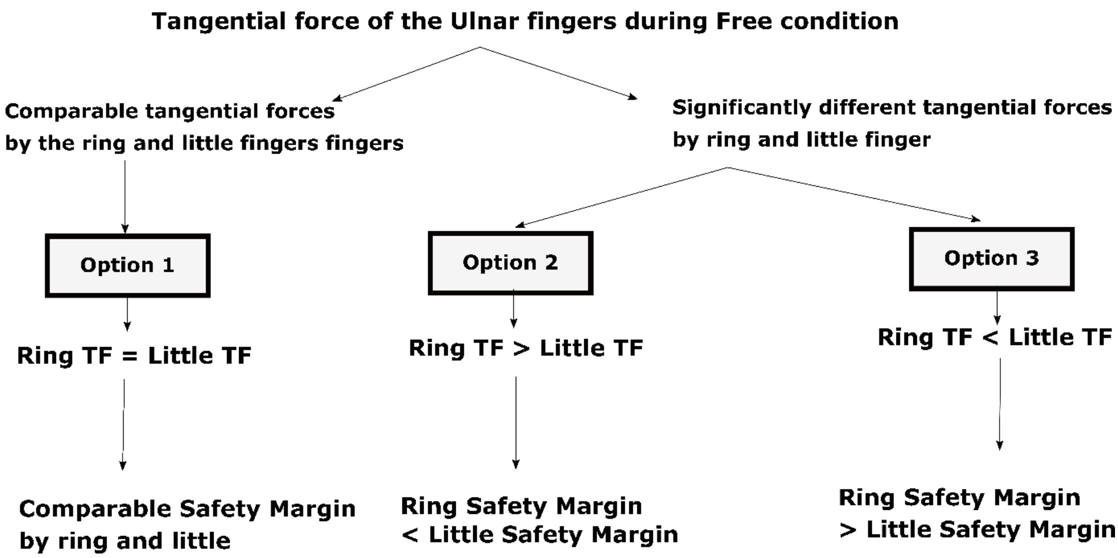

Figure 2.17 Different possibilities of tangential force distribution and safety margin among the Ulnar fingers (ring and little) Three different possible ways by which tangential force (TF) among the ring and little fingers can vary are shown. Option 1: To produce comparable tangential forces by the ring and little fingers, Option 2: To produce significantly greater tangential force by the ring finger than the little finger, Option 3: To produce significantly greater load force by the small finger than the ring finger. If Option 1 is preferred by the CNS, the safety margin of the ring and little finger will also be comparable. If Option 2 is chosen, the safety margin of the ring finger would be lesser than the little finger. If Option 3 is selected, the safety margin of the ring finger would be greater than the little finger

In contrast, there were few other studies that examined the tangential force distribution among the fingers during the grasping of a handle [28]. According to their results, the little finger exerts greater tangential force than the ring finger. In a prehension study [15], when the surface friction at the thumb-object interface was reduced by using low friction contact material such as rayon, the little finger showed a rise in the tangential force that reached statistical significance. Similarly, middle and ring fingers also showed a rise in the tangential force, but they failed to reach statistical significance. Based on Aoki's study, it is probable that the CNS could even choose the third option. However, this was not supported by the findings on the normal forces. As the result on normal forces does not comply with the mechanical advantage hypothesis [25], the suspicion on the little finger sharing greater tangential force than the ring finger narrowed. Because if there is a greater tangential force exerted by the small finger, in order to maintain the safety margin of the same finger, the grip force of the little finger also tends to increase, which would probably be greater than the ring finger. But, in contradiction, the normal force of the ulnar fingers was comparable. So, it was thought that the chances of the little finger producing greater tangential force than the ring finger was lesser.

In reality, the tangential forces of the ulnar fingers were statistically comparable (i.e., Option 1). The reason for adopting the first option could have been due to the position of the thumb platform while grasping. This could be explained from a biomechanical standpoint. Followed by the current study, there was another study performed with the same handle [63]. The participants were asked to trace the “trapezoid” and “inverted trapezoid” pattern displayed on the monitor by translating the thumb in the vertical direction, either upwards or downwards from the HOME. The amount of displacement of the thumb remained the same (1.5 cm) in both directions from HOME. During the trapezoid tracing condition, when the thumb reached 1.5 cm above the HOME, it was found that the tangential force of the ring finger was greater than the little finger. Similarly, during inverted trapezoid tracing condition, when the thumb reached 1.5 cm below the HOME, the little finger tangential force was greater than the ring finger. During both the conditions, they were required to keep the handle in equilibrium (even when there is a shift in the thumb position). It was speculated that the biomechanical association between the little finger and thumb might have caused significant changes in the ulnar finger load forces.

When the thumb was translated upwards, there occurs an abduction of the carpometacarpal joint (CMC) of the thumb [64], [65]. The abduction movement of the thumb might have resulted in the radial deviation of the wrist, which could be restricted by an ulnar deviation (resisting action) caused by the abduction of the little finger [66], [67]. Thus, the abduction might have been accompanied by the abduction of the little finger, which occurs in the form of rotation towards medial side while grasping. Therefore, the location of force application of the little finger tends to shift downwards. Hence, it was speculated that the reason for the greater reduction in the tangential force of the small finger (compared to other fingers) might be due to the resisting action of the little fingertip in the downward direction. Likewise, when the thumb was translated downwards, the opposition movement of the CMC joint of the thumb could be accompanied by an opposition act of a little finger that occurs in the form of lateral rotation[66]. Therefore, the little finger exhibiting a rise in tangential force when compared to the other fingers.

However, when the thumb remained at the HOME, there was no necessity for the resisting action to be produced by the little finger, which might be a reason for the little finger to exert a comparable tangential force. Thus, it was understood that the central nervous system was involved in activating the resistive reaction in the little finger when there was an active action of the thumb. This was visible from the fingertip forces of the respective fingers. Since there was a comparable tangential and grip force exerted by the ulnar fingers, the safety margin was also statistically equivalent. This shows that the system does not consider the strength of the finger to share the forces in this particular task. Instead, it adapts to choose an economical way of sharing the forces when the thumb is comfortably positioned at the HOME.

As the thumb was kept on a slider platform, proprioceptors on the thumb detect the frictional change under the slider. The CNS, in turn, responds by necessitating the mechanical action of lowering the tangential force of the thumb. The magnitude of thumb tangential force in free condition depended on the mass of the thumb platform. Hence, this is considered to be the first local change that initiated the synergic effect in the ring and little finger. In the current study, the following chain effect was observed during the free condition: mechanical constraint to fix the thumb in position was removed→ load force of the thumb decreases → VF tangential force increases → rise in the counter-clockwise moment → counterbalanced by the rise in the grip force of ulnar fingers → moment due to normal force of ulnar fingers increases in the clockwise direction to counterbalance the rise in the counter-clockwise moment → increase in the normal force of ulnar fingers were compensated by the rise in thumb's normal force. Thus, the change in the load force of the thumb resulted in the re-arrangement of the normal force of all the fingers. This is evident from Figure 2.7, where it was observed that an rise in the percentage change in the grip forces of all the fingers and thumb in free condition compared to the fixed condition. The local change of drop-in thumb load force results in the tilting of the handle in the counter-clockwise direction [68]. Meanwhile, the synergic change of increasing the normal forces of the ulnar fingers brings about a compensatory tilt in the opposite direction. Therefore, it 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.

Comparable grip forces exerted by the two ulnar fingers may be attributed to at least two distinct factors: biomechanical constraints and neural interdependency. Biomechanical constraints include the mechanical linkages and the tendinous interconnections. Firstly, the main source of the gripping force in the ulnar fingers was exerted by the Flexor Digitorum Profundus (FDP). The tendons of the FDP muscle extend from the forearm to the tip of all fingers (except thumb). These tendons are responsible for flexion of the distal interphalangeal joint to exert appropriate normal forces. Since the tendons of the middle, ring, and little fingers share a common muscle belly, at the forearm level, contraction of one portion (or compartment) of the FDP muscle could cause shortening of the neighboring muscle compartment of the same FDP. Thus, the mechanical linkage between the muscle compartments of FDP restricts the independent rise in the grip force of the target finger. Secondly, at the palmar level, it is found that there is a tough fibrous sheet that interconnects the tendons of the middle, ring, and little fingers [69]. Therefore, during the free condition, the flexion of the small finger (to cause an rise in the grip force of the small finger) to overcome tangential force drop in the thumb would be accompanied by the flexion of the adjacent ring finger probably as a result of interconnection between the tendons.

Apart from the biomechanical effects, there also exists an overlap in the motor units territories of the ulnar fingers at the medial portion of the FDP muscle, which is responsible for the flexion of ulnar fingers [70]. In a following study [71], during the weak voluntary grasping of a cylindrical object, forces were measured under each finger. It was shown that the forces measured under the ring finger due to the activity of small finger motor units was almost two-thirds of that force produced under the small finger due to the small finger motor units. This change in force caused by the small finger motor units under the ring finger was significantly greater ($p<0.001$) than the change in force produced by index, middle, ring motor units under their adjacent fingers.

As there is a necessity to compensate for the drop in the clockwise moment caused by the tangential force of thumb, little finger motor units get activated (because of the longer moment arm of the small finger) to cause flexion (or rise in grip force) of the little finger. Subsequently, perhaps this results in the activation of the little finger motor units found at the ring finger portion of FDP muscle. Apart from the increase in the normal force of the ulnar fingers due to the little finger motor units, the normal force of the ring finger increases due to the activation of ring finger motor units. Hence, this distinct behavior of the activation of little finger motor units (on small and ring finger portion of FDP muscle) and ring finger motor units on ring finger portion of FDP could be a reason for the exertion of significantly comparable normal force by the ulnar fingers.

2.6 Conclusion

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 grip force of ring and little finger. It was evident from the current study that the ring and little finger normal force showed a statistically comparable increase to counteract the drop in the thumb load force. Thus, the little finger (one of the peripheral fingers) did not produce a 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 the index and middle finger in the free condition compared to the fixed condition. The results of this study can serve as input towards the development of robotic hands that involve operating hand tools that require vertical motion of the thumb for the operation. 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 the middle or ring finger) by mounting it on the unsteady platform.

CHAPTER 3.

ULNAR FINGER CONTRIBUTION WITH SYSTEMATIC INCREASE IN HANDLE MASS

3.1 INTRODUCTION

Previously, studies were involved in investigating the force contribution of the individual fingers and thumb when systematic variations (or perturbations) were imparted to the properties of the grasped handle. Such variations involved introducing external torques [30], [45], [72], [73], varying the mass of the external loads [40], [43], surface friction modification[74]–[76], alteration to the grip width of the handle [14] or individual digit width [34] in the horizontal direction, and change in the position of the fingertips [44] and the thumb [45] while grasping.

Grip and load forces of the individual fingers and thumb varied systematically in response to these perturbations. Some of these perturbations also disturbed the rotational equilibrium of the handle. In such situations, compensatory torque production was required by the fingers to sustain the handle in static equilibrium. Considering the position of the thumb as pivot point (located midway between middle and ring finger) while grasping a handle, peripheral fingers (index and little) have longer moment arm for normal force than the central fingers (middle and ring) with shorter moment arm for the normal force. According to the mechanical advantage hypothesis (MAH) [31], [33], during compensatory moment production tasks, for example, when there is a requirement to produce supination moment (or torque) in the clockwise direction, little finger with longer moment arm for normal force tends to produce greater normal force than its neighboring ring finger with shorter moment arm for normal force. Thus, by utilizing the mechanical advantage of the little finger, the total force produced by the ulnar fingers could be reduced without compromising on the required moment[77].

Several studies have attempted to examine the applicability of the mechanical advantage principle for a five-finger grasping task. Mechanical advantage hypothesis was supported in tasks that involved handle rotation in the pronation and supination directions at two different speeds [57], the addition of an external load of different masses at varying distances from the center of mass of the handle [14], and moment production to follow a trapezoid template by pressing with all four fingers [78]. However, the hypothesis was only partially supported in a moment production task on a object that was fixed mechanically [29], where the distance from the fingers to the axis of rotation, magnitude, and direction of torque production was varied systematically. The authors of the afore-mentioned study posited that the applicability of the MAH may be task and effector-specific. As such, it is yet unclear what kind of tasks the applicability of MAH depends on. Therefore, it is necessary to investigate whether the applicability of mechanical advantage is task-specific and which kind of tasks/scenarios support the MAH.

In the previous study of the current research, the applicability of MAH was investigated by introducing torque changes to the handle [79]. Rather than implementing external torque changes by suspending the load at a distance from the center of mass of the handle, torque changes were incorporated by reducing friction between the thumb platform and the handle interface. This was made possible by placing the thumb on a slider platform that could freely translate vertically over a railing. In this way, the tangential force produced by the thumb was kept constant and less than the virtual finger [80] (an imaginary finger whose mechanical output is equal to the combined output of the individual fingers except for the thumb). This had resulted in introducing a residual pronation torque to the handle. Since the instruction was to maintain the handle in static equilibrium, a compensatory supination torque was required to avoid the tilt caused as a result of the residual pronation torque. Ulnar finger normal forces and thumb tangential forces are major contributors to this compensatory supination torque. However, by the current handle design, it was not possible to increase the tangential force of the thumb as it had to hold the slider platform steady at the HOME position (midway between middle and ring fingers). Therefore, only the grip forces produced by the ulnar fingers became the primary source of this compensatory supination torque.

Between the ulnar fingers, the little finger has a larger moment arm for normal force when compared with the ring finger. Hence it was expected that the little finger would produce greater normal force. Contrary to this expectation, ring and little fingers were found to share comparable normal forces while grasping the handle of mass 0.535kg [79]. Therefore, in the current study, the expectation was that MAH would be corroborated if the mass of the handle was increased systematically by adding different external loads. As per the design of this grip device, the tangential force of the thumb was constrained to a constant minimal magnitude. So, with an increase in the mass of the handle, only the tangential force of the virtual finger increases, which is accompanied by an increase in the residual pronation torque. As a corrective effect, the magnitude of compensatory supination torque required to be produced would also increase. Hence, it was expected that with a systematic increase in the mass of the handle, the little finger would produce correspondingly higher normal force than the ring finger during compensatory supination torque production.

In line with such an expectation, in the current study, the mass of the handle was systematically increased by employing external loads of mass 0.150, 0.250, 0.350, and 0.450kg as different experimental conditions. A previous study had shown comparable normal forces between the ulnar fingers for a handle mass of 0.535kg [79]. In another study on investigating the role of grasp force magnitude during multi-finger prehension [36], by suspending an external load of mass 0.160kg eccentrically at various distances under a handle of mass 0.415kg, the contribution of digit forces in terms of percentage of total normal force of the virtual finger was examined. It was found that even for a small external torque of 0.14 Nm, during natural grasping, the percentage share of the small finger normal force (approx. 45%) was greater than the ring finger normal force (approx. 33%).

The total mass of the handle (0.450kg) with the minimum external load (0.150kg) used in the current study was approximately close to the total mass of the grip device in the afore-mentioned multi-finger prehension study [36]. Hence, it was hypothesized that the mechanical advantage hypothesis would be supported for all experimental conditions (0.150kg, 0.250kg, 0.350kg, and 0.450kg) of external load starting with a minimal mass of 0.150kg (Hypothesis H1).

3.2 Materials and Methods

3.2.1 Participants

Twelve young, right-handed healthy male volunteers participated in this study. The mean and standard deviation of the participant's age, height, weight, hand length and width were measured as following: Age: 26.75±3.9 years, Height: 172.02±5.7cm, Weight: 75.21±17.7kg, Hand-length: 18.93±1.1cm, and Hand-width: 8.92±0.7cm). Only participants with no previous history of neurological diseases and musculoskeletal injuries were chosen to participate in this experiment.

3.2.2 Ethics approval

All the participants gave written informed consent according to the procedure approved by the institutional ethics committee of IIT Madras (Approval Number: **IEC/2021-01/SKM/02/05)** before the beginning the experiment.

3.2.3 Experimental setup

A five-finger prehensile handle was designed and custom-built for the experiment, as shown in Figure 3.1. The handle consists of a vertical railing of length 13.6 cm fitted on the thumb side to mount the slider platform, thus allowing its vertical translation along the railing. The handle was suspended from wooden support using a nylon rope housed within a hollow PVC pipe to restrict any undesirable lateral movement while it was suspended. The present study involves a prismatic precision grip of the handle of mass 0.450kg. The mass of the slider platform was 0.100 kg. Thus, restricting the thumb tangential force to approximately 1N. Five six-axis force/torque sensors (Nano 17, Force resolution: Tangential: 0.0125N, Normal: 0.0125N) was mounted on the handle to measure the forces and the moments exerted by the individual fingers and thumb. For the thumb alone, the force sensor was placed on the slider platform, which enabled the smooth translation of the platform over the railing fitted on the handle's thumb side.

A laser displacement sensor (resolution, 5µm; OADM 12U6460, Baumer, India) was mounted on a square flat piece made of acrylic, and the assembly was fitted on top of the handle towards the thumb side. The displacement sensor provided the displacement data of the thumb platform in the vertical direction while it translated along the vertical railing. On top of the handle, another acrylic block was placed in the anterior-posterior direction, which held an intelligent 9-axis absolute orientation sensor (Resolution: 16bits, Range: 2000º/s, Model: BNO055, BOSCH, Germany). This IMU (Inertial Measurement Unit) sensor provided the orientation data of the handle after appropriate pre-processing of the raw data. A spirit level was also mounted on the acrylic block towards the participant’s side of the handle to aid the participant in ensuring the handle’s vertical orientation while it was being held.

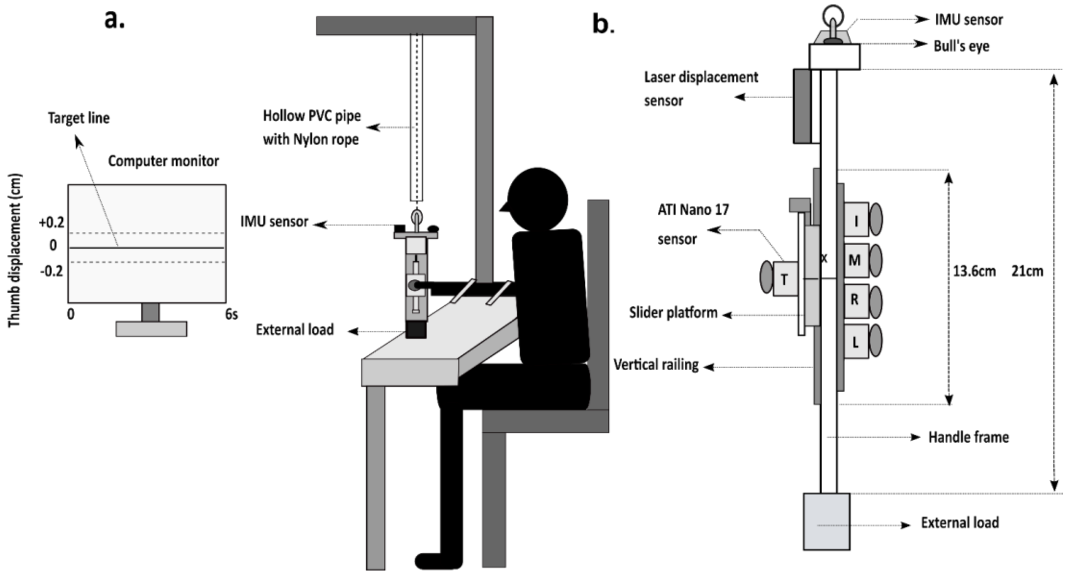

Figure 3.1 Schematic diagram of the experimental setup and five-finger prehensile handle. A. Experimental setup with the participant holding the handle at a distance of 1.5m away from the computer monitor. The handle was suspended from a wooden support using a nylon rope housed within the hollow PVC pipe to restrict the lateral movements of the handle. The solid horizontal target line was shown on the computer monitor with two dashed lines that represented an acceptable error margin. B. Schematic diagram of the experimental handle. The aluminum handle frame (21 x 1 x 3) cm with five fingertip force (ATI Nano 17) sensors, laser displacement sensor, and orientation measuring sensor (IMU) are shown. The grip aperture of the handle is 6.2cm. External loads of 0.150kg, 0.250kg, 0.350kg, and 0.450kg were attached at the bottom of the handle (i.e.) below the center of mass (represented as 'X') of the handle. I, M, R, L, T represents Index, Middle, Ring, Little, and Thumb.

Two horizontal lines were drawn on the participant's side of the handle, one at the center of the thumb platform and another midway between middle and ring fingers on the handle frame. The participants were asked to hold the handle in a way such that the two lines were aligned. Signals from the force/torque sensors and single-channel analog laser displacement data were digitized using NI USB 6225 and 6002 (National Instruments, Austin, TX, USA). This data was synchronized with four channels of processed, digital data from the IMU sensor. Sampling rates of all data were set to 100Hz

3.2.4 Experimental procedure

Participants were asked to wash and clean their hands with soap, towel-dry and then sit comfortably on a wooden chair with their forearm resting on the table. 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 involved four conditions. For these conditions, external loads of mass 0.150kg, 0.250kg, 0.350kg, and 0.450kg were added at the bottom of the handle, i.e., exactly under the center of mass of the handle. A computer monitor displayed a solid horizontal target line with two dashed lines at 0.2cm above and below the target line. These dashed lines represented an acceptable error margin. The target line shown on the monitor corresponded to the 'HOME position' of the thumb. The trial began only after the participant could hold the thumb platform steadily by aligning the horizontal line on the thumb platform to the line drawn midway between the middle and ring finger. Thumb displacement data measured using a laser displacement sensor was shown as feedback on the participant's screen. Once the trial started, the participants were required to keep the slider platform in the same position (HOME), by aligning the horizontal line on the platform to the line drawn between the central fingers. Precise alignment of the two lines during the task essentially meant that the feedback line traced the actual target line. Acceptable performance or task success during the trial was defined to be within an error margin of ±0.2cm as mentioned above. Throughout the trial, the handle had to be maintained in static equilibrium in the frontal plane for all the external loads. This was ensured by having the bubble of the spirit level at the center throughout the trial.

For each experimental condition, 25 trials were performed. Each trial lasted for six seconds. One minute of break was provided between trials. After every twelve trials, ten minutes of break was provided to eliminate the effect of fatigue, if any. The experiment was held in two separate sessions. Each session included two external load conditions with thirty minutes of break between different loads. The order of these two sessions was counterbalanced across all participants. Six of the participants performed with the weight of 0.150kg followed by 0.350kg in their first session. The other six participants performed with the weight of 0.450kg followed by 0.250kg in their first session.

3.3 Data Analysis

The data was analysed using Matlab (Version R2016b, MathWorks, USA). Force/Torque data and laser displacement data of thumb were lowpass filtered at 15Hz. The data between 2s and 5s was taken for analysis to avoid start and end effects.

3.3.1 Average normal and tangential force

The normal and tangential force data collected from the individual fingertips and thumb were averaged over the time samples, trials and participants for each condition separately and their standard error of mean was also computed.

3.3.2 Statistics

All Statistical analyses were performed using R. Two-way repeated-measures ANOVA was performed on the average normal force with the two factors being *loads* (4 levels: 0.150kg, 0.250kg, 0.350kg, 0.450kg) and *fingers* (4 levels: index, middle, ring, little). Since the thumb normal force is dependent on the grip forces of the index, middle, ring, and little fingers, a separate one-way repeated measures ANOVA was performed on the thumb normal force with the factor as *loads* (4 levels: 0.150kg, 0.250kg, 0.350kg, 0.450kg). Another two-way repeated-measures ANOVA was performed on the average tangential force with the factors being *loads* (4 levels: 0.150kg, 0.250kg, 0.350kg, 0.450kg) and *fingers* (5 levels: index, middle, ring, little, thumb). Sphericity test was done on the data, and the number of degrees of freedom was adjusted by Huynh-Feldt (H-F) criterion wherever required. Pairwise post hoc tukey tests were performed to examine the significance within factors. Further, equivalence tests were performed for all the non-different pairs. The statistical equivalence was tested using the two one-sided t-tests (TOST) approach [59] for a desired statistical power of 95%. The smallest effect size of interest (SESOI) was chosen as the equivalence bounds.

3.4 Results

3.4.1 Task performance

All the participants were able to trace the horizontal target line shown on the monitor within the error margin during all four loading conditions (0.150kg, 0.250kg, 0.350kg, and 0.450kg), as shown in Figure 3.2. Root mean squared error (RMSE) on the thumb displacement data was computed for the four different loads and is shown in Table 3.1. Throughout the trial, the participants attempted to maintain the handle at static equilibrium during all four loading conditions by positioning the bubble at the center of the bull's eye. Therefore, the average net tilt angles for the different loading conditions were found to be less than one degree, as shown in Table 3.1. Thus, the participants could trace the target line with minimal vertical displacement and minimal tilt during all trials in all loading conditions.

Table 3.1 Root Mean Square Error on the thumb displacement data and Net tilt angle. The table shows the average net tilt angle measured in degrees and root mean square error (RMSE) in cm on the thumb displacement data with standard deviation for the four different loads 0.150kg, 0.250kg, 0.350kg, and 0.450kg.

Additional Loads (kg)	Net tilt angle (degrees) (mean±SD)	RMSE on the thumb displacement data (cm) (mean±SD)
0.150	0.58±0.22	0.0215±0.0054
0.250	0.73±0.19	0.0246±0.0066
0.350	0.70±0.15	0.0240±0.0071
0.450	0.81±0.23	0.0325±0.0185

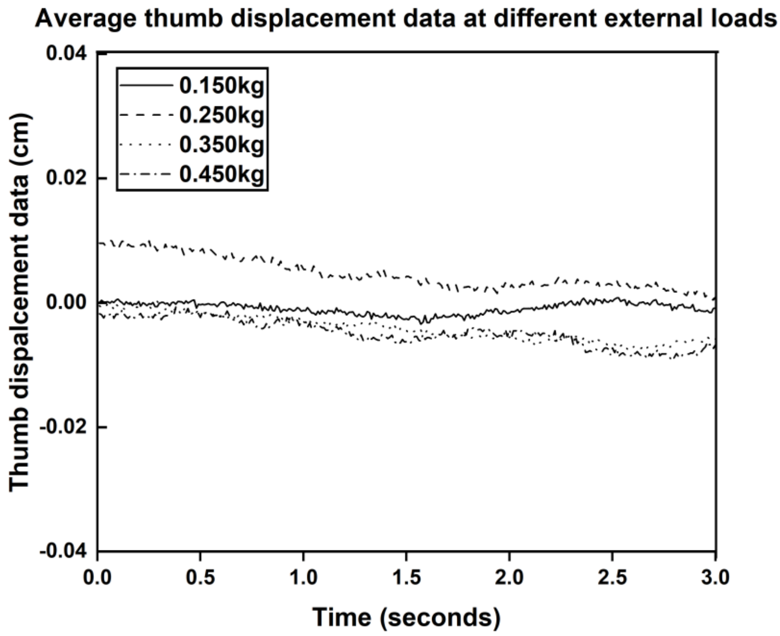

Figure 3.2 Average thumb displacement data at different load conditions. Each line plot represents the average taken across trials and participants during the addition of each external load. The solid horizontal target line displayed on the computer monitor appears at 0cm (not shown in this figure for the sake of clarity). X axis represents the time in seconds. Only the data from 2s to 5s for analysis (sampling frequency =100Hz) is shown here. The average thumb displacement data collected in each condition was found to remain closer to the 0cm (i.e target line).

3.4.2 Grip forces of individual fingers and thumb during different loads

The grip forces of the ulnar fingers were found to be statistically comparable with the addition of external loads of 0.150kg, 0.250kg, and 0.350kg. However, when an external load of 0.450kg was added, the little finger normal force was found to be statistically ($p<0.0001$) greater than the ring finger normal force and thus supporting MAH (see Figure 3.3).

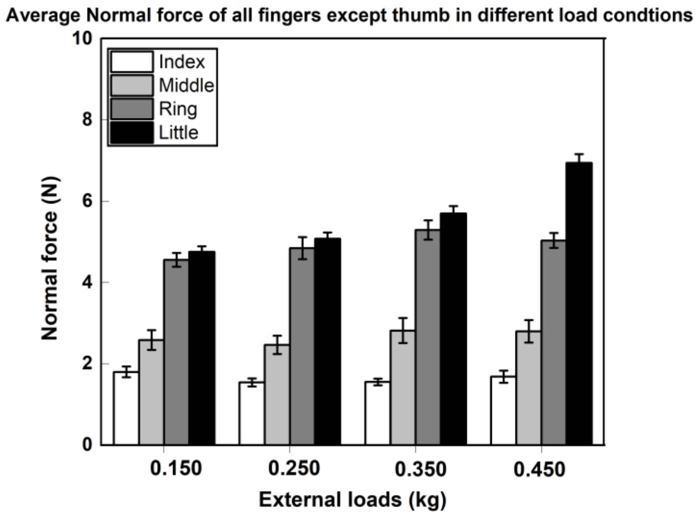

Figure 3.3 Average Normal force of Index, Middle, Ring, and Little fingers under different loading conditions. Little finger normal force (represented in black) was found to be statistically ($p<0.0001$) greater than the ring finger normal force (represented in dark shaded grey) in the 0.450kg loading condition. The ring and little finger normal forces were found to be statistically equivalent under remaining loading conditions. The columns and bars indicate means and standard errors of means.

A main effect of the factor *loads* ($F_{(2.73, 30.03)}= 8.571$; $p<0.001$, $\eta^2_p=0.43$) was observed when a two-way repeated-measures ANOVA was performed on the absolute normal force with the factors as *loads* and *fingers*. It was found that the normal forces of the individual fingers (excluding the thumb) under the loading condition of **0.450kg** were statistically ($p<0.001$) greater than the normal forces produced under loading conditions of **0.150kg** and **0.250kg**. Further, the normal forces produced with a load of **0.350kg** were statistically ($p<0.05$) greater than the normal force produced with a load of **0.150kg.** In addition to this, there was a significant effect of the *fingers* ($F_{(3, 33)}= 181.921$; $p<0.001$, $\eta^2_p=0.94$) corresponding to a statistically ($p<0.001$) higher normal force by the little finger than the index, middle and ring fingers on loading. Also, the normal force of the ring finger was statistically greater than the index and middle fingers.

Meanwhile, it was also found that the ring and little finger normal forces were non-different when external loads of masses **0.150kg** (t(11) = -1.129, p = 0.283, d_z=0.32), **0.250kg** (t(11) = -0.978, p = 0.349, d_z=0.28) and **0.350kg** (t(11) = -1.454, p = 0.174, d_z =0.41) were employed. Therefore, by using TOST procedure on the dependent pairs (**0.150Kg**: Ring: Mean=4.55N, SD=0.55; Little: Mean=4.75N, SD=0.45; **0.250kg**: Ring: Mean=4.84N, SD=0.90; Little: Mean=5.07N, SD=0.50; **0.350kg** : Ring: Mean=5.29N, SD=0.78; Little: Mean=5.70N, SD=0.58), it was confirmed that the ring and little fingers normal forces were statistically equivalent (**0.150kg**: t(11) = 2.473, p = 0.0155; **0.250kg**: t(11) = 2.625, p = 0.0118; **0.350kg:** t(11) = 2.148, p = 0.0274) with the observed effect size that falls within the equivalence bounds of Δ_L=-1.04 and Δ_U=1.04 under the loads of 0.150 kg, 0.250 kg and 0.350 kg.

The interaction *loads* x *fingers* was significant ($F_{(3.96, 43.56)}$= 18.538; p<0.001, η^2_p=0.62) reflecting the fact that the ring and little finger normal forces of **0.450kg** (Ring: 5.03N, Little: 6.94N), **0.350kg** (Ring: 5.29N, Little: 5.70N), **0.250kg** (Ring: 4.84N; Little: 5.07N), were statistically (p<0.001) greater than the index and middle finger normal forces (**0.150kg**: Index: 1.79N, Middle: 2.58N; **0.250kg**: Index: 1.54N, Middle: 2.46N; **0.350kg**: Index: 1.55N, Middle: 2.81N; **0.450kg**: Index: 1.68N, Middle: 2.79N) of all the loading conditions (refer Figure 3.4).

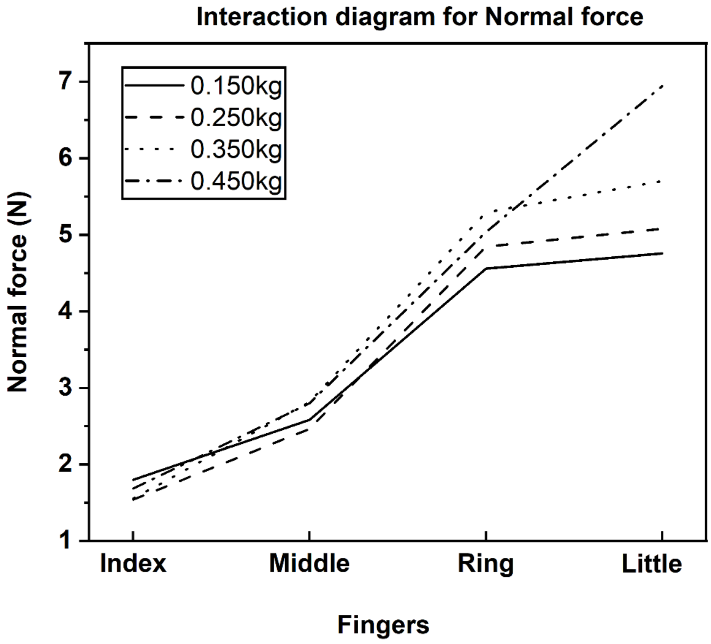

Figure 3.4 Interaction between loads and finger normal forces The pairwise post hoc tukey tests confirmed that the ring and little finger normal forces of 0.450kg (Ring: 5.03N, Little: 6.94N) 0.350kg (Ring: 5.29N, Little: 5.70N), 0.250kg (Ring: 4.84N; Little: 5.07N) were statistically greater than the index and middle finger normal forces (0.150kg: Index: 1.79N, Middle: 2.58N; 0.250kg: Index: 1.54N, Middle: 2.46N; 0.350kg: Index: 1.55N, Middle: 2.81N; 0.450kg: Index: 1.68N, Middle: 2.79N) of all the loading conditions

While, the pairwise post hoc tukey tests confirmed that the little finger normal force (6.94N) of **0.450kg** was statistically ($p<0.001$) greater than the ring and little finger normal forces (**0.150kg**: Ring: 4.55N, Little: 4.75N; **0.250kg**: Ring: 4.84N, Little: 5.07N; **0.350kg**: Ring: 5.29N, Little: 5.70N ($p<0.01$)) of the remaining loads. Whereas a little finger **(**5.70N) of **0.350kg** produced statistically ($p<0.01$) greater normal force than the ring finger (4.55N) under **0.150kg** of load.

One-way repeated-measures ANOVA was performed on the thumb normal force, which showed a significant effect of the factor loads ($F_{(2.69,\ 88.90)}= 9.411$; $p<0.001$,

η^2_p=0.46). Under the loading of **0.450kg**, the thumb normal force (16.50N) was found to be statistically greater than under loadings of **0.150kg** (13.73N, p<0.01) and **0.250kg** (13.97N, p<0.05)) (refer Figure 3.5)

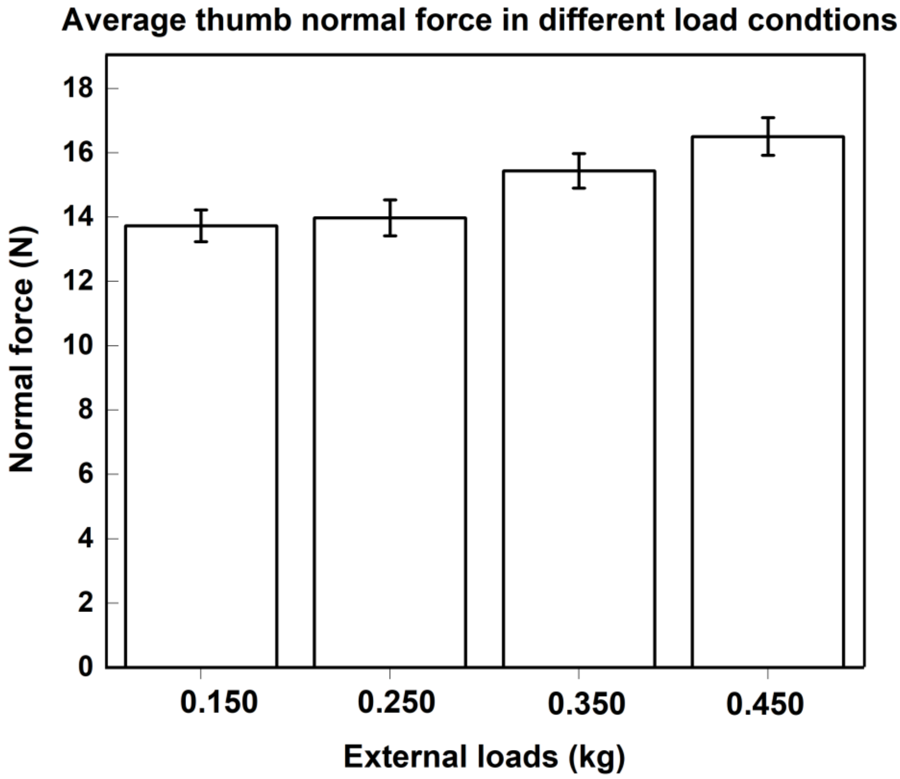

Figure 3.5 Average normal force of the thumb under different loading conditions The thumb normal force (16.50N) with an addition of external load of 0.450kg was found to be statistically greater than the thumb normal force under the loadings of 0.150kg (13.73N) and 0.250kg (13.97N). Further, the thumb normal force (16.50N) at 0.450kg load was statistically equivalent to the thumb normal force (15.44N) with the load of 0.350kg.

3.4.3 Tangential forces of individual fingers and thumb during different loads

In the case of the tangential forces, a two-way repeated-measures ANOVA with the factors as *loads* ($F_{(3, 33)}$= 390.575; p<0.001, η^2_p=0.97) and *fingers* ($F_{(4, 44)}$= 44.205; p <

0.001, $\eta^2_p = 0.80$) showed significant effect of the factor *loads* corresponding to a statistically greater tangential force with the use of **0.450kg** than with the use of **0.150kg** ($p < 0.001$), **0.250kg** ($p < 0.001$), **0.350kg** ($p < 0.05$) loads. In addition, a significant effect of the factor *fingers* confirmed that the little finger tangential force was statistically ($p<0.001$) greater than the index, middle, and ring finger tangential forces on loading.

In addition to this, on performing the pairwise post hoc tukey test, it was confirmed that the little finger tangential force (**0.150kg**: 2.03N, **0.350kg**: 2.80N) was non-different from the ring finger tangential force during the employment of **0.150kg** (1.64N) and **0.350kg** (2.26N). TOST procedure performed on these dependent pairs confirmed that the comparisons were not statistically equivalent. However, little finger tangential force (**0.450kg**: 3.22N; **0.250kg**: 2.54N) was statistically greater than the ring finger tangential force with the addition of load **0.450kg** (Ring: 2.52N, $p<0.01$) and **0.250kg** (Ring: 1.92N, $p < 0.05$) (see Figure 3.6).

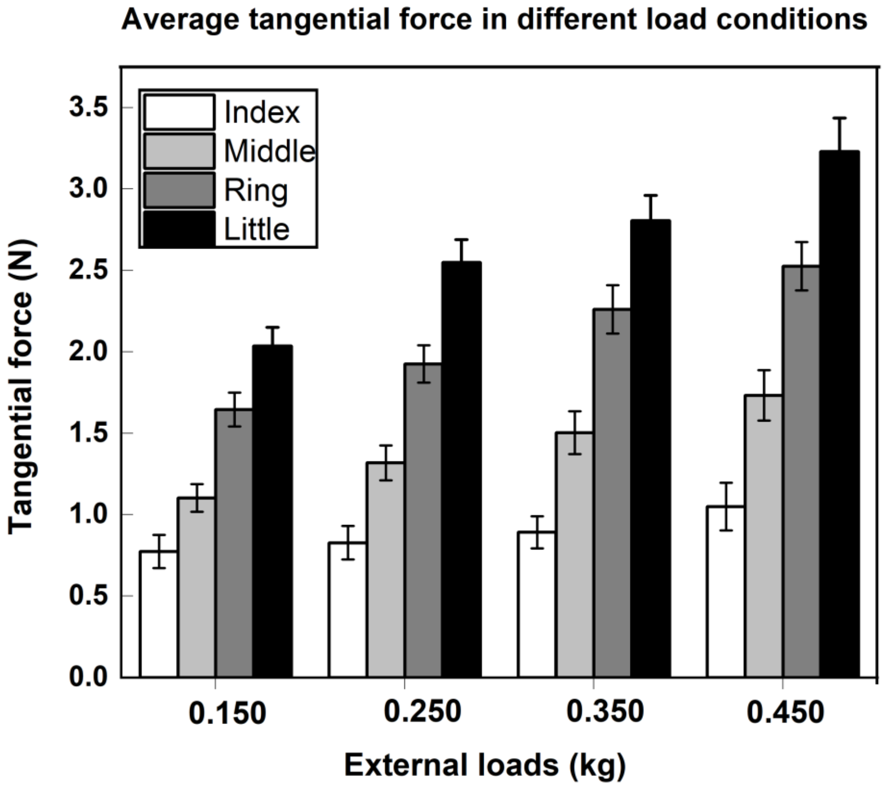

Figure 3.6 Average tangential force of Index, Middle, Ring, and Little under different loading conditions. Little finger tangential force (0.250kg: 2.54N; 0.450kg: 3.22N) was found to be statistically greater than the ring finger tangential force (0.250kg: 1.92N; 0.450kg: 2.52N) under 0.250kg ($p < 0.05$) and 0.450kg ($p < 0.01$) loading conditions. In particular, the little finger tangential forces (3.22N) of 0.450kg was statistically greater than the little finger tangential forces (0.150kg: Little: 2.03N; 0.250kg: Little: 2.54N) of 0.150kg and 0.250kg. The columns and bars indicate the means and standard errors of means.

Further, interaction effect of *loads* x *fingers* was significant ($F_{(12, 132)}$= 5.857; $p<0.001$, η^2_p=0.34) reflecting the fact that the little finger tangential forces (3.22N) due to the use of **0.450kg** was statistically greater than the ring and little fingers tangential forces (**0.150kg:** Ring: 1.64N, $p<0.01$, Little: 2.03N, $p<0.001$; **0.250kg:** Ring:1.92N, $p<0.001$, Little: 2.54N, p<0.05; **0.350kg:** Ring: 2.26N, p<0.001) due to the other loads (refer Figure 3.7).

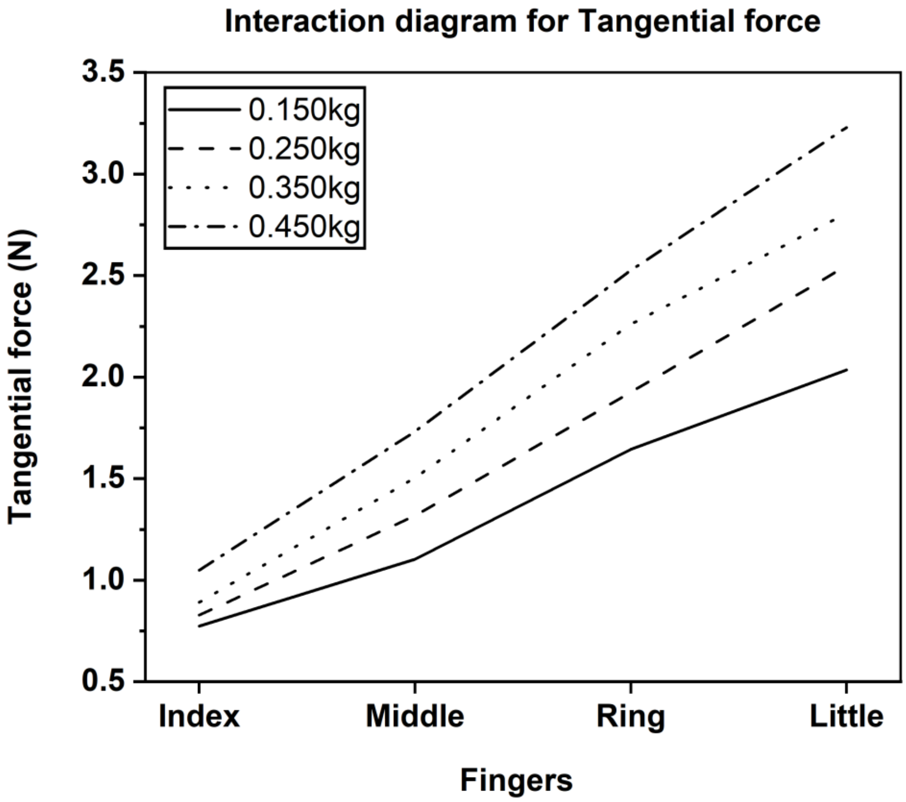

Figure 3.7 Interaction between loads and finger tangential forces The little finger tangential force (3.22N) with the use of external load of 0.450kg was statistically greater than the ulnar fingers tangential forces (0.150kg: Ring: 1.64N, Little: 2.03N; 0.250kg: Ring:1.92N, Little: 2.54N) under the loadings of 0.150kg & 0.250kg. Also, the little finger tangential force (3.22N) at 0.450kg was statistically greater than the ring finger tangential force (2.26N) when a load of 0.350kg was added.

3.5 Discussion

The main objective of the present study was to investigate whether the applicability of MAH is dependent solely on task parameters like the total weight of the handle, moment arm of the suspended load, or is it affected by factors beyond these physical parameters.

MAH was tested by systematically increasing the weight of the handle by adding external loads at the bottom of the handle below its center of mass. The weight of the current handle with the minimal loading condition exceeded the weight of the handle in the previous study[79]. So, it was hypothesized that MAH would be supported in all loading conditions. Contrary to the expectation, it was found that the ulnar finger normal forces were statistically comparable with the addition of 0.150kg, 0.250kg, and 0.350kg loads. However, it was noticed that MAH was supported for the external load of 0.450kg. The implications of these findings were discussed in the following paragraphs.

Ulnar finger normal forces were examined under four different external loading conditions i.e., 0.150kg, 0.250kg, 0.350kg and 0.450kg. In the previous study[79], with a similar unsteady thumb platform as used in the current study, the ulnar fingers produced comparable normal forces for a handle mass of 0.535kg. With the minimal external load of 0.150kg, the total mass of the handle would become 0.600kg (above 0.535kg that was used in the previous study). So, the expectation was that MAH would be supported for all the loading conditions. In contrast to the expectation, the little finger produced statistically comparable normal forces to the ring finger for 0.150kg load. With further increase in the external loadings with masses 0.250kg and 0.350kg, the ulnar fingers exhibited statistically comparable normal forces. However, this trend did not hold true when the external load was increased to 0.450kg, wherein the little finger exerted a statistically greater normal force than the ring finger.

Unlike the other studies on grasping with eccentrically loaded manipulanda, the current study involved maintaining a constant minimal tangential force by the thumb (approximately 1N) at different loading conditions (see Figure 3.8).

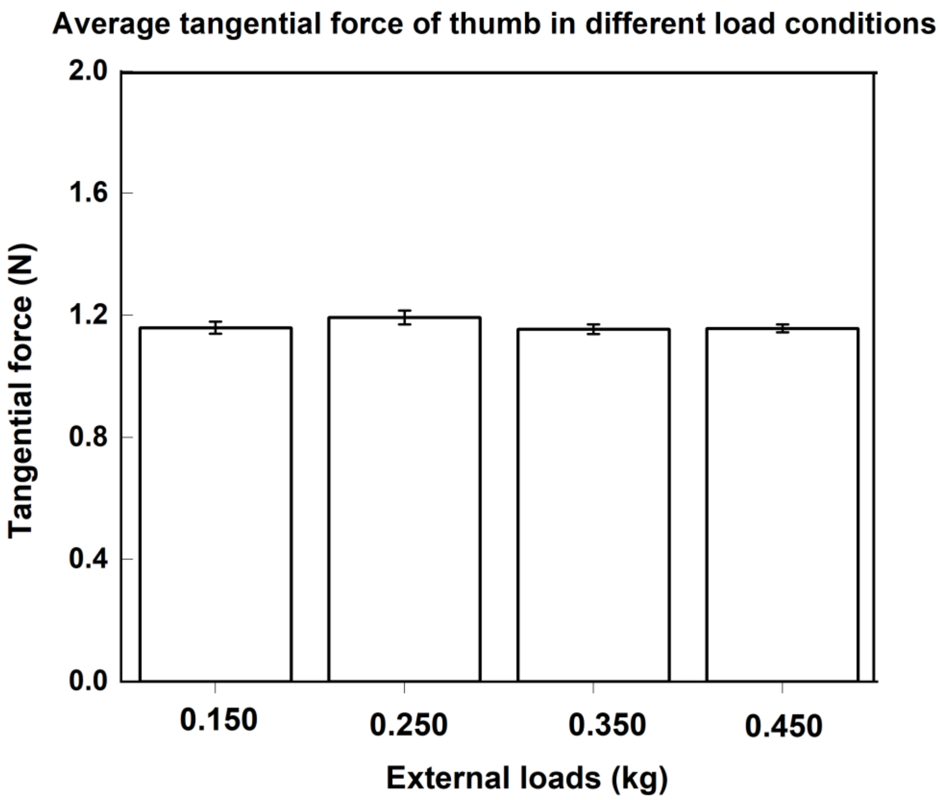

Figure 3.8 Average tangential force of thumb under different loading conditions Thumb tangential force at different conditions was found to be statistically comparable

Therefore, with an increase in the total mass of the handle by adding an external load of 0.450kg (comparatively larger than the mass of other loads employed in the present study), the virtual finger had to share greater tangential force to maintain the vertical equilibrium causing a greater pronation torque (counter-clockwise direction from the participants viewpoint). This, in turn, necessitated a progressively greater compensatory supination moment to establish the equilibrium. Since the design of the handle prevents the thumb from contributing further to the supination moment, the ulnar fingers are required to compensate with their normal forces. In this regard, instead of exerting comparable normal forces, the small finger tends to produce higher grip force than the ring finger, thus supporting MAH. What could be the reason for this behavior of ulnar fingers with the inclusion of the heaviest external load as compared to the other loads?

A natural question is whether the applicability of mechanical advantage depends on employing heavy masses while grasping. If that had been true, then MAH would have been supported when a large external load of 2kg was suspended at a distance of 1.9cm from the center of mass (COM) of the handle (for a torque magnitude of -0.375Nm) in the grasping study investigating the contribution of peripheral and central fingers[25]. However, they found that ulnar fingers normal forces were non-different for this large load. Eventually, with a systematic increase in the compensatory supination torque magnitude (0.750Nm, 1.125Nm, and 1.50Nm), the little finger gradually started producing more normal force than the ring finger and validated the MAH.

In another study investigating the role of grasp force magnitude during multi-finger prehension[36], when an external load of mass 0.160kg (much lesser than 2kg) was suspended from a handle of mass 0.415kg eccentrically at a distance of 8.9cm from COM, MAH was supported. This result triggers another question as to whether the support for MAH depends on suspending the external load at large moment arms from COM of the handle? From the results of the multi-finger prehension study[36], it was apparent that the applicability of mechanical advantage depends on using higher moment arms for the external load. The current result forces us to re-evaluate this conclusion, as MAH was supported even when an external load of 0.450kg was suspended directly below the COM of the handle (having zero moment arm). This suggests that apart from the mass of the external load and moment arm of the suspended load, a latent factor governs the applicability of mechanical advantage. In other words, this data suggest that the applicability of the principle of mechanical advantage in biological systems depends not only on the mass or moment arm of the suspended load or both but also on more individual-specific components such as the individual ability of managing a task.

In the prehension study evaluating the effect of grasp force magnitude [36], the challenging aspect of the task might have been using an unusually high moment arm, thus allowing MAH to manifest. In a recent study[63] using a handle similar to the current study, the task was to trace trapezoid and inverted trapezoid patterns by displacing the thumb platform 1.5cm above and below the HOME position. The mechanical advantage hypothesis was supported during the inverted trapezoid condition when the movable thumb platform was held steady while tracing the static portion 1.5cm below the HOME (at the level below the center of the ring finger sensor). The carpometacarpal joint (CMC) of the thumb has a restricted range of motion in the downward direction[64] (flexion or radial adduction). Therefore, the task of maintaining the handle in static equilibrium with a movable thumb platform at the level below the center of the ring finger sensor might have been quite difficult to perform. It was suggested that this biomechanical constraint which imparted difficulty in accomplishing the task might have caused the little finger to share higher grip force than the ring finger.

Following a similar rationale, in the current study, perhaps the task became fairly demanding, as the requirement was to produce compensatory supination torque with only the normal forces of the ulnar fingers. This was a direct effect of restricting the thumb tangential force to a constant minimal magnitude and essentially rendering it much less consequential in the supination torque production. Simultaneously, this also amplified the role of the ulnar fingers in the compensatory torque production. For the heaviest external load of 0.450 kg, the magnitude of fingertip forces required were much higher than the magnitude of fingertip forces in the relatively easier loading conditions i.e., for the 0.150 kg, 0.250kg, 0.350kg loads. According to a study that investigated the use of mechanical advantage in multi-finger torque production [77], MAH is employed to lessen the overall effort or force produced for the task without compromising to produce the required moment. Along similar lines, it was speculated that to avoid higher exertion (higher force levels) of the ulnar fingers by sharing comparable and greater forces (due to tangential force restriction in the thumb), the participants used the mechanical advantage of the little finger to more efficiently manage the grasp after a threshold difficulty was reached. As per the instruction to participants in the current study, the participants were allowed to continue performing the trials only when they did not feel over exertion or pain. Therefore, to successfully complete the task, without indulging in straining the ring and little fingers, participants would have chosen to minimize the total force (or effort) in the ulnar fingers by employing the principle of mechanical advantage.

Also, from literature [81], it was found that by excluding the small finger from the overall grip dropped overall grip strength by 33%, and excluding the ring finger from the overall grip dropped overall grip strength by 21%. This shows that, among the ring and little fingers, little finger contribution is fairly higher than the ring finger when there is an increase in overall grip force requirement. Thus, an addition of heavier external load, which in turn increases overall grip force requirement, might have caused the little finger to contribute significantly greater than the ring finger. From an anatomical perspective, the little finger has an additional group of intrinsic muscles (hypothenar muscles) compared to the ring finger, which could be a supporting factor to employ little finger than ring finger when the task becomes difficult or demanding.

To further elucidate the current result, it is important to emphasize that in the previous studies on object manipulation that introduced external torques to the handle, there was no restriction in the distribution of load forces among the fingers and the thumb while grasping. The tangential force of the thumb would have greatly contributed to the supination torque in addition to the normal forces of the ulnar fingers. This was evident from the previous study[25], where the thumb tangential force increased during the supination efforts. Hence, the participants might have been able to share comparable grip forces by the ring and little fingers even with a larger load (2kg) and with a greater torque magnitude of 0.375Nm than in the current study.

In contrast, in the current study, the tangential force of the thumb was restricted to approximately 1N by placing the thumb on a freely movable platform of mass 0.100kg for all the loading conditions. This essentially creates a situation wherein the ulnar fingers are forced to contribute greatly to the compensatory supination torque. Such a constraint in the tangential force contribution of the thumb presents a great sense of challenge to the participant. This is most exemplified under 0.450 kg external load. Note that this load is much less than the 2kg load where MAH was not supported. It was strongly believed that individual-specific components such as the individual ability of managing a task that is difficult to accomplish might have encouraged the use of the mechanical advantage of the little finger. The difficulty faced by the performer is not dictated merely by the external loads and torques but also due to the biomechanical constraint as in the previous study[63], or it could be due to the individual's ability of managing a task.

In the present study, the participants could complete the task under loads of 0.150kg, 0.250kg, and 0.350kg (resulting in the supination torques of 0.22Nm, 0.23Nm, and 0.25Nm, respectively), which might not be difficult challenging enough than a load of mass 0.450kg (refer Figure 3.9 and Figure 3.10). As under a load of mass 0.450kg, the task of maintaining the static equilibrium of the handle by producing greater and comparable forces by the ulnar fingers might have been difficult. Therefore, for successful completion of the task, little finger having both mechanical and anatomical advantage would have produced greater force than ring finger. Whereas, due to the task simplicity, comparable normal forces would be produced by the ulnar fingers, with the addition of 0.150kg, 0.250kg, and 0.350kg loads.

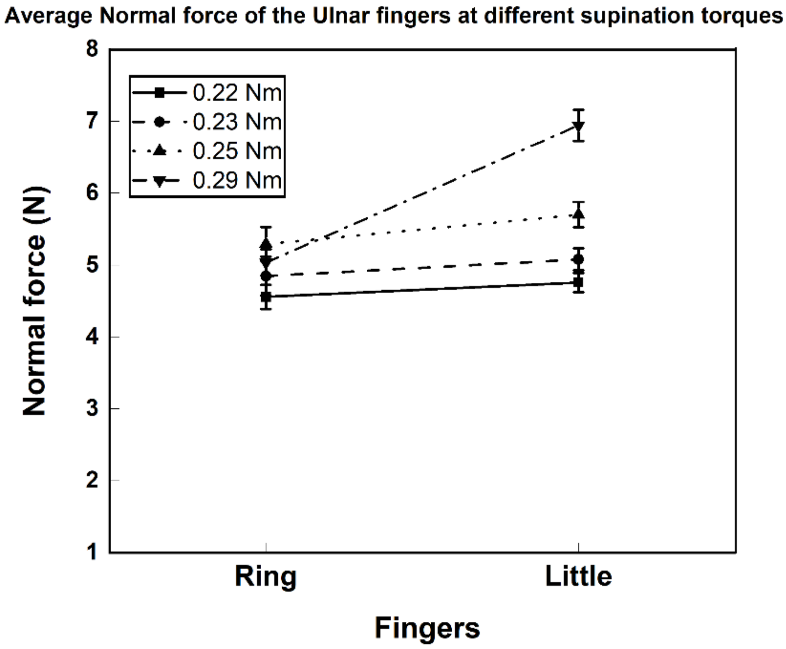

Figure 3.9 Normal forces of the ring and little fingers for supination efforts under different loading conditions/supination torque requirement. For 0.29 Nm torque requirement (represented by dashes with dots), the normal force of the little finger was found to be statistically greater than the ring finger normal force. In all the other conditions, ring and little fingers produced comparable normal force. The bars indicate standard errors of means.

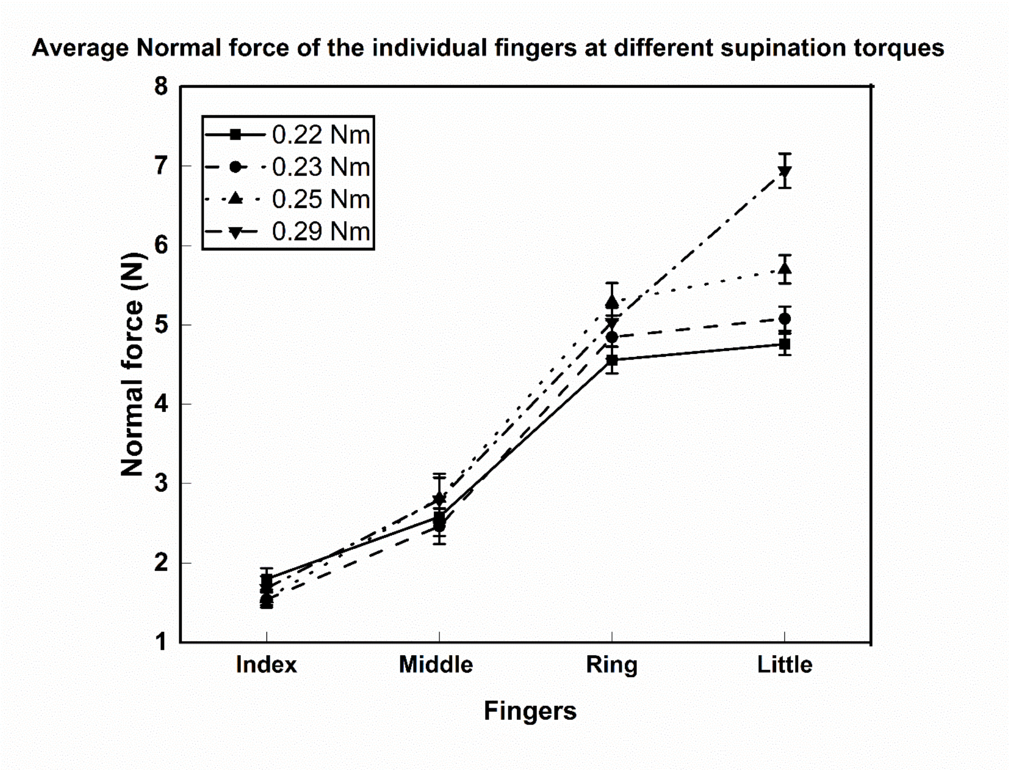

Figure 3.10 Relationship between individual finger normal force and finger for supination efforts under different loading conditions/supination torque requirement. The results of the pairwise post hoc Tukey tests confirmed that the little finger normal force (6.94N) due to the addition of 0.450kg load was statistically greater than the ring (0.150kg: 4.55N; 0.250kg: 4.84N; 0.350kg: 5.29N; 0.450kg: 5.03N) finger normal force due to the addition of all four different loads. Further, the little finger normal force with the use of 0.450kg was found to be statistically greater than the little finger (0.150kg: 4.75N; 0.250kg: 5.07N; 0.350kg: 5.70N) normal forces due to addition of other loads.

In a study on producing maximum voluntary contraction MVC[82], when the target finger is the little finger, the force produced by the little finger was found to be well above the adjacent ring finger force. Analogously, since the current study involved very strong voluntary grasping of the handle for the external loading condition of 0.450kg, greater activation of the little finger motor units could have caused a greater force in the little finger than the ring finger, thus enabling optimal distribution of forces within the ulnar fingers in line with the MAH. This is also supported by the study[71] wherein they found that the magnitude of force produced due to the little finger motor units under the ring finger was almost two-thirds of the force produced under the little finger during voluntary grasping. Since the actual activation pattern of the individual motor units was not measured, further research is required to tease out the underlying neural mechanisms through which mechanical advantage is manifested. Taken together, the results on the current study suggest that the applicability of the mechanical advantage hypothesis depends not only on the torque requirement or the total mass of the object but also on the individual’s ability to manage the task.

3.6 Conclusion

The current study was performed to validate whether the mechanical advantage hypothesis is task-specific and investigate the kind of task the MAH depends on. A five-finger prehensile handle with an unsteady thumb platform was utilized for analyzing the applicability of MAH. The mass of the handle was systematically increased by using additional external loads of mass 0.150kg, 0.250kg, 0.350kg, and 0.450kg. Ulnar fingers exerted a comparable normal force with the external loads of mass 0.150kg, 0.250kg, and 0.350kg. However, the mechanical advantage hypothesis was supported with a load of 0.450kg. With the addition of greater mass, under the constraint of minimal thumb tangential force, establishing static equilibrium by the ulnar fingers becomes progressively more challenging. Thus, MAH is a strategy utilized in human grasping and is not only employed when there is any change in the mass of the grasped handle or moment arm of the suspended load but also when a certain threshold difficulty is reached during the task.

CHAPTER 4.

EVIDENCE TO SUPPORT MECHANICAL ADVANTAGE HYPOTHESIS OF GRASPING AT LOW FORCE LEVELS

4.1 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 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 [39], torque [45], fingertip position[44], and surface friction [43] of the object were varied systematically. During any torque changes to the handheld object, the mechanical advantage of the fingers has been employed to minimize the total effort (or force) [77]. With regard 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) [25]. The instruction was to maintain the handle at 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 [57], [78]. In a multi-finger torque production study [77], 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, the 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 [79]. 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 the expectation, ulnar fingers exerted statistically comparable normal forces when the unsteady thumb platform was held steady at the HOME position.

The mechanical advantage hypothesis was partially supported by a study involving moment production on a mechanically fixed vertically oriented handle [29]. 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, it was 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, the 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[83]. 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, it was speculated that to avoid higher exertion (or higher force levels) of the ulnar fingers by sharing comparable and greater forces, the participants used the mechanical advantage of the little finger to more efficiently manage the grasp after a threshold difficulty was reached.

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 grip 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 at 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 the system 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, it was hypothesized that the mechanical advantage of the little finger would be utilized 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).

4.2 Materials And Methods

4.2.1 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.

4.2.2 Ethics approval

All the participants gave written informed consent according to the procedure approved by the institutional ethics committee of IIT Madras (Approval Number: **IEC/2021-01/SKM/02/05)** before the start of the experiment.

4.2.3 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 Figure 4.1). 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) were mounted on the handle to measure the individual fingers and thumb forces. 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: 2000°/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. Signals from the force/torque sensors and single-channel analog laser displacement data were digitized using NI USB 6225 and 6002 (National Instruments, Austin, TX, USA). This data was synchronized with four channels of processed, digital data from the IMU sensor.

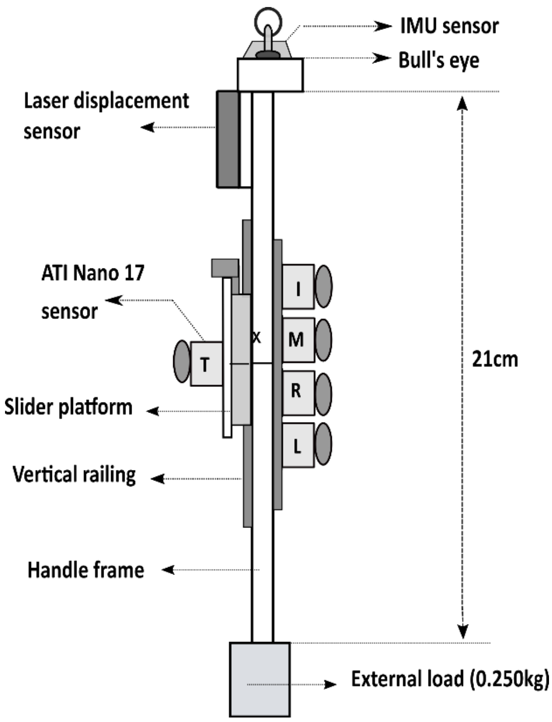

Figure 4.1 Schematic diagram of the experimental handle. The figure shows the schematic diagram of the experimental handle with the slider platform on the thumb side of the handle. The handle was made of an aluminum handle frame (21 x 1 x 3) cm with a slider platform mounted over the vertical railing 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.

4.2.4 Experimental procedure

Participants washed their hands with soap and towel dried before the start of the experiment. 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 at 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 Figure 4.2). 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.

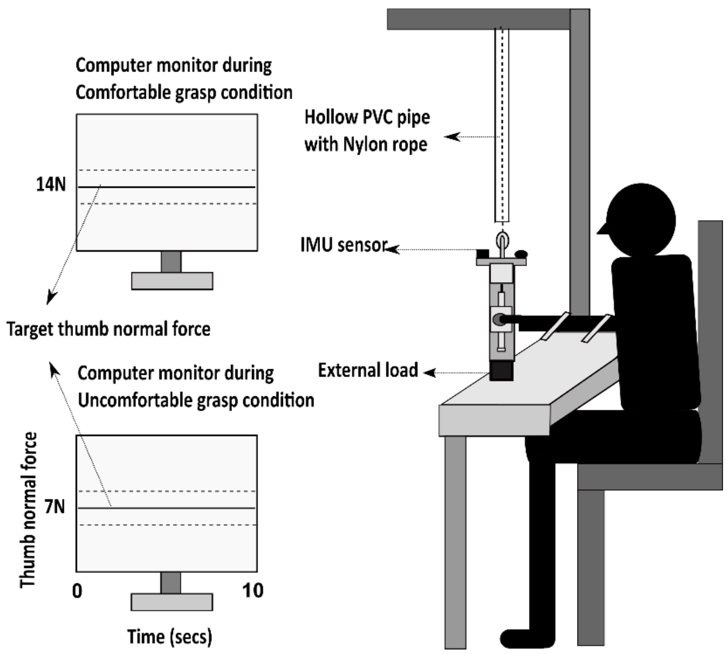

Figure 4.2 Schematics of a participant performing the experiment. The figure shows the experimental setup with a participant holding the experimental handle in front of the computer monitor. The monitor displayed a solid horizontal line that corresponded to the target normal force to be produced by the 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.

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, grip and load 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.

4.3 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 analysed using MATLAB (Version R2016b, MathWorks, USA). Force/Torque data and laser displacement data of thumb were lowpass filtered at 15Hz. The 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.

4.3.1 Statistical analysis

All statistical analyses were performed using R. A two-way repeated-measures ANOVA was performed 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. 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[59] for a desired statistical power of 95%. The smallest effect size of interest (SESOI) was chosen as the equivalence bounds.

4.4 Results

4.4.1 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 4.1. 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 4.1.

Table 4.1 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

4.4.2 Normal forces of individual fingers and thumb during different grasps

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 Figure 4.3).

A two-way repeated-measures ANOVA was performed 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 ring and little fingers compared to the index and middle 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 ring and little 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 index and middle finger normal forces of both comfortable (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.

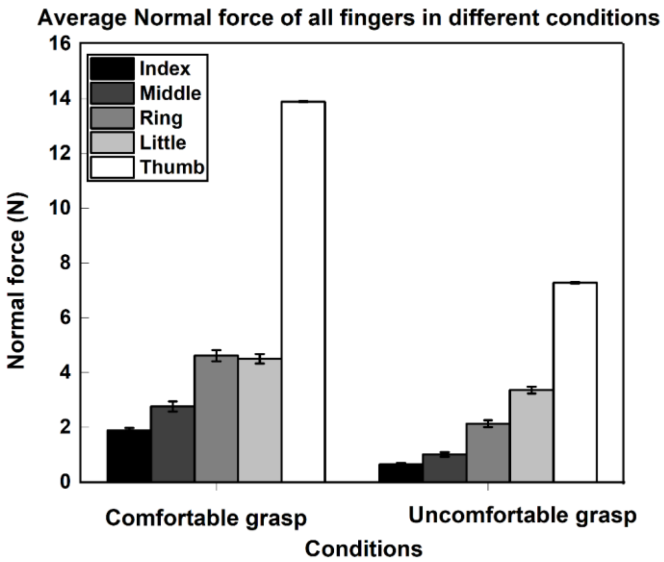

Figure 4.3 Average Normal forces of the individual fingers and thumb in different conditions. Little finger normal force (represented in light shaded gray) of comfortable grasp condition was statistically equivalent to the ring finger normal force (represented in medium shaded gray) of the same condition. 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.

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 ring and little 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.

4.5 Discussion

The idea of the present study was to check and confirm whether the support for the mechanical advantage principle depends on the individual’s ability of managing a task situation. The little finger produced a higher grip force than the ring finger when the thumb was restricted to produce a normal force of 7N closer to the mass of the handle. It was believed that the reason could be due to the difficulty 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[84]. 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[36]. 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.

The 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[83]. 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 individual’s ability of managing a task or difficulty 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[63]. 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 difficulty 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 the 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, it was 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 weight 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 (μ ~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 difficult 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 the preliminary study[79], 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 grip forces decreased. The drop 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 rise 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 grip 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 all fingers (except thumb). 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[85]–[87].

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 (hypothenar) 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, the little finger might have been utilized 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 difficult, as in the current study.

4.6 Conclusion

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, the system might have decided to use the little finger to complete the task successfully. Thus, the challenge associated with the task had induced to use the little finger, supporting the mechanical advantage hypothesis, by producing greater normal force in the little finger than the ring finger.

CHAPTER 5.

BIOMECHANICAL RELATIONSHIP BETWEEN THE THUMB AND LITTLE FINGER

5.1 Introduction

From literature, it is known that the role played by the peripheral fingers differs from the central fingers according to the task requirement [25]. The forces generated by the central fingers varied depending on both the load and torque changes to the grasped object. In contrast, studies have reported an rise in the grip forces of peripheral fingers for the tasks that required the maintenance of the rotational equilibrium of the handle[57], [78]. Hence, the peripheral fingers were given special attention when torque changes were introduced to the handheld object.

In the preliminary study[79], torque changes were incorporated in the handle by placing the thumb on a slider platform matching the midline between middle and ring fingers. Since the mechanical constraint to fix the slider platform was removed, the load force of the thumb dropped. In order to compensate for the drop, a supination moment was required to be produced by the rest of the fingers. Although it was expected that the little finger would contribute to produce greater normal force, the ulnar fingers exerted a comparable normal force. However, the grip forces exerted by the ulnar fingers were greater than the normal forces exerted by the radial fingers, as expected.

From these studies, it is evident that the contribution of the fingers varied depending on the objects handled. Certain objects in real life require vertical motion of the thumb for their operation. For example, while aspirating a sample fluid using specific models of pipette controllers, the pipette has to be held in a vertical orientation while making a fine vertical adjustment using the thumb. In such tasks, the participation of peripheral fingertip forces is critical in producing greater normal force to overcome the torque changes due to the thumb translation. This idea of providing freedom to the thumb emerged by observing the working of such objects that have a vertical tuner on the thumb side for their operation. Thus, in the current study, a handle with an unsteady thumb platform was designed to examine the contribution of index and little finger forces in re-establishing the rotational equilibrium due to thumb motion.

Some studies have examined the individual fingertip forces at discrete locations of the thumb during the static holding of the handle[45]. Still now none of these studies have examined the force distribution of peripheral fingers when the thumb is mounted on an unsteady platform and held at different positions. This study will give a better understanding of the morphological relationship of the peripheral fingers with the thumb to overcome the torque changes caused due to the unsteady thumb platform held at various positions. The task involved moving this thumb platform towards index (referred as 'TOP'), and little (referred as 'BOTTOM') finger ends.

Due to the vertical translation of the thumb platform towards the index and little finger end from the HOME position, there are at least four possible ways by which normal forces of the peripheral fingers may or may not vary to maintain the rotational equilibrium (refer Figure 5.1). In a previous study[25], where there was a shift in the position of external load, there was a requirement to produce compensating torques to restore handle equilibrium. Index finger produced greater *change* in the normal force when “pronation” torques than the little finger did when “supination” torques. Since, in the current study, the little finger had already produced greater normal force than index to maintain the handle in equilibrium when the thumb was at HOME, the suspicion was that the shift in thumb position might not cause the little finger to show greater *change* as it is the weakest finger (at least in terms of maximum voluntary contraction (MVC) forces).

Therefore, according to first and fourth option, the *change* in the grip force of the index when the platform was displaced from HOME to TOP (during trapezoid condition) would be greater than the *change* in the grip force of the little finger when the thumb was moved from HOME to BOTTOM (during inverted trapezoid condition) position. Note that among the four digits (I, M, R, L), index finger is the strongest [88] (in terms of MVC forces). The only difference between the first and last option was the absolute grip force by the peripheral fingers when the thumb was held at the TOP and BOTTOM position. In the first option, the absolute grip force produced by the index finger will be comparable to the little finger while in the last option, the absolute grip force of index finger will be higher than the little finger.

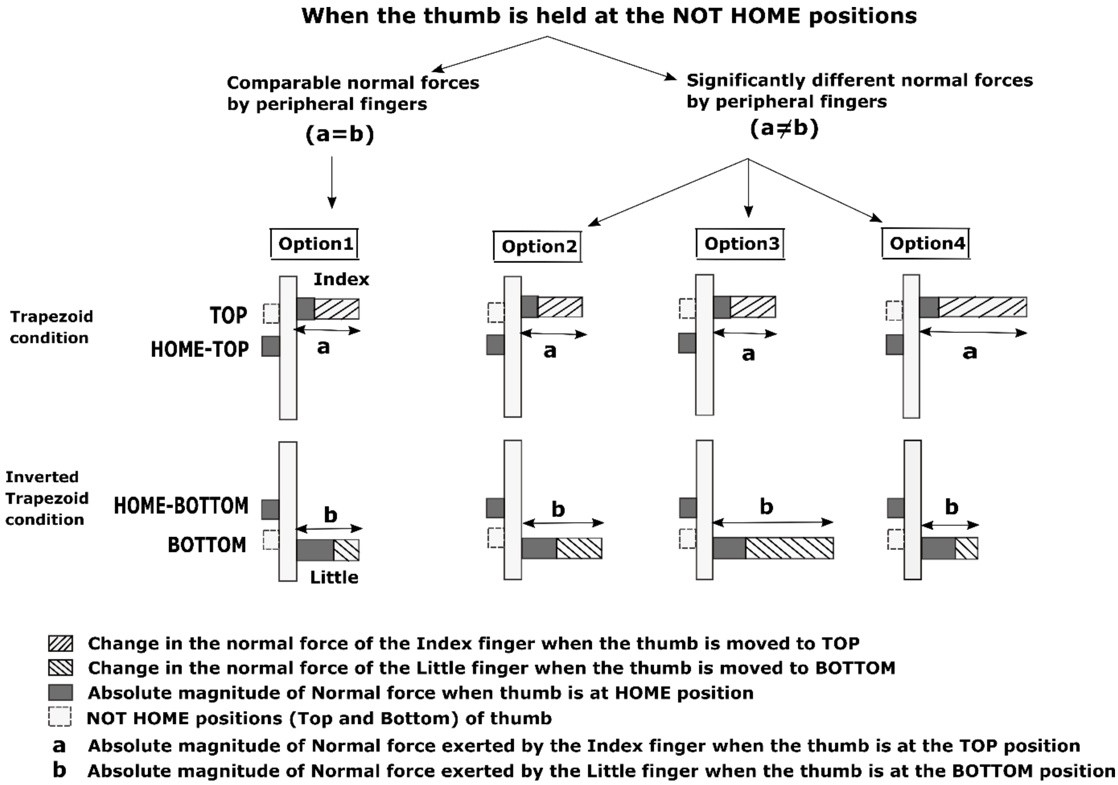

Figure 5.1 Pictorial representation of four different options. This figure shows the absolute normal force of the peripheral fingers when the thumb is held at different positions and the *change* in the normal force experienced by the peripheral fingers when the thumb shifted to the NOT HOME positions from HOME during the static balance of the handle. In all four options, the absolute normal force exerted by the little finger will be greater than the index finger when the thumb stays at the HOME (indicated in dark grey). Option 1: During trapezoid condition, when the thumb translates to the TOP from HOME, *change* in the normal force of the index finger (right oriented lines) will be significantly greater than the *change* in the normal force of the little finger (left oriented lines) when the thumb translates to the BOTTOM from HOME during the inverted trapezoid condition. Thus, the absolute normal force produced by index finger (indicated as ‘a’) when the thumb is held static at the TOP position (dashed line) will be equivalent to the absolute normal force produced by little finger (indicated as ‘b’) when the thumb is held static at the BOTTOM. Option 2: The *change* in the normal force of the peripheral fingers will be equivalent. However, the absolute normal force produced by the little finger when the thumb is at the BOTTOM will be greater than the index finger when the thumb is at the TOP. Option 3: The *change* in the index finger normal force will be significantly lesser than the *change* in the little finger normal force. Thus, the absolute normal force produced by the index finger when the thumb is at the TOP will be significantly lesser than the little finger normal force when the thumb is at the BOTTOM. Option 4: The *change* in the index finger normal force will be significantly greater than the change in the little

> finger normal force. And, the absolute normal force produced by the index finger when thumb remains at the TOP will be significantly greater than the little finger normal force when the thumb remains at the BOTTOM

In the current study, the thumb was displaced to a level above the center of the middle finger sensor during the trapezoid condition and a level below the center of ring finger sensor during the inverted trapezoid condition. Therefore, this study was compared with the study that investigated the force sharing pattern in multi-finger tasks [24], where there was a comparable *change* in the percentage of the peripheral fingers normal force when the center of the thumb was placed above and below the middle and ring finger level. Thus, with regard to the second option, it was suspected that it is also possible for the peripheral fingers to exert comparable *change* in the normal force when the thumb was displaced slightly above and below the level of middle and ring finger sensor center. So, the absolute normal force of little finger would be higher than index.

Based on the same study [24], when the thumb locations were altered, the *change* in the percentage of little finger normal force by placing thumb at the level of ring finger sensor center was greater than the *change* in the index finger normal force when the thumb was placed at the center of middle finger sensor. Similarly, it might also be possible for the little finger to show greater *change* in the grip force when the thumb was shifted to the BOTTOM position than the index finger when the thumb was shifted to TOP position. Therefore, this was considered as the third option where the absolute normal force of little finger would be higher than index when the thumb was at the NOT HOME positions.

Since, in the present study, the thumb was displaced to a level above and below the central fingers sensor's center, it was expected that the second option would most likely be true. Hence, it was hypothesized that the *change* in the normal forces of the peripheral fingers would be comparable (Hypothesis H1). Also, it was anticipated that there would be a rise in the grip force of the thumb to compensate for the rise in the grip force of the peripheral fingers when the thumb moved away from HOME. For this reason, it was hypothesized that the thumb normal force would show a significant increase when the thumb platform reached various positions away from HOME (Hypothesis H2).

5.2 Materials and Methods

5.2.1 Participants

Twelve right-hand dominant male volunteers (mean ± standard deviation Age: 22.6±2.4 years, Height:173.4±6.4cm, Weight:70.5.3±9.7kg, Hand-length:19±0.6cm, and Hand-width:9.5±0.6cm) participated in this study. Participants did not have any history of hand injuries or neurological disorders.

5.2.2 Ethics approval

The experimental conditions were sanctioned by the Ethics committee of IIT Madras (Approval number: IEC/2018-03/SKM-2/05). Consent form was collected from all participants before the beginning of the experiment.

5.2.3 Experimental setup

An instrumented five-finger prehension handle made of aluminum was designed for performing this experiment, shown in Figure 5.2. The thumb side of the handle had a vertical railing over which a slider platform was placed fingertip forces and moments were measured by mounting five six-component force/torque sensors (Model Nano 17, Force resolution: Tangential: 0.0125N, Normal: 0.0125N, ATI Industrial Automation, NC, USA). The sensor for the thumb was mounted on the slider platform, and other sensors were mounted on the side without railing.

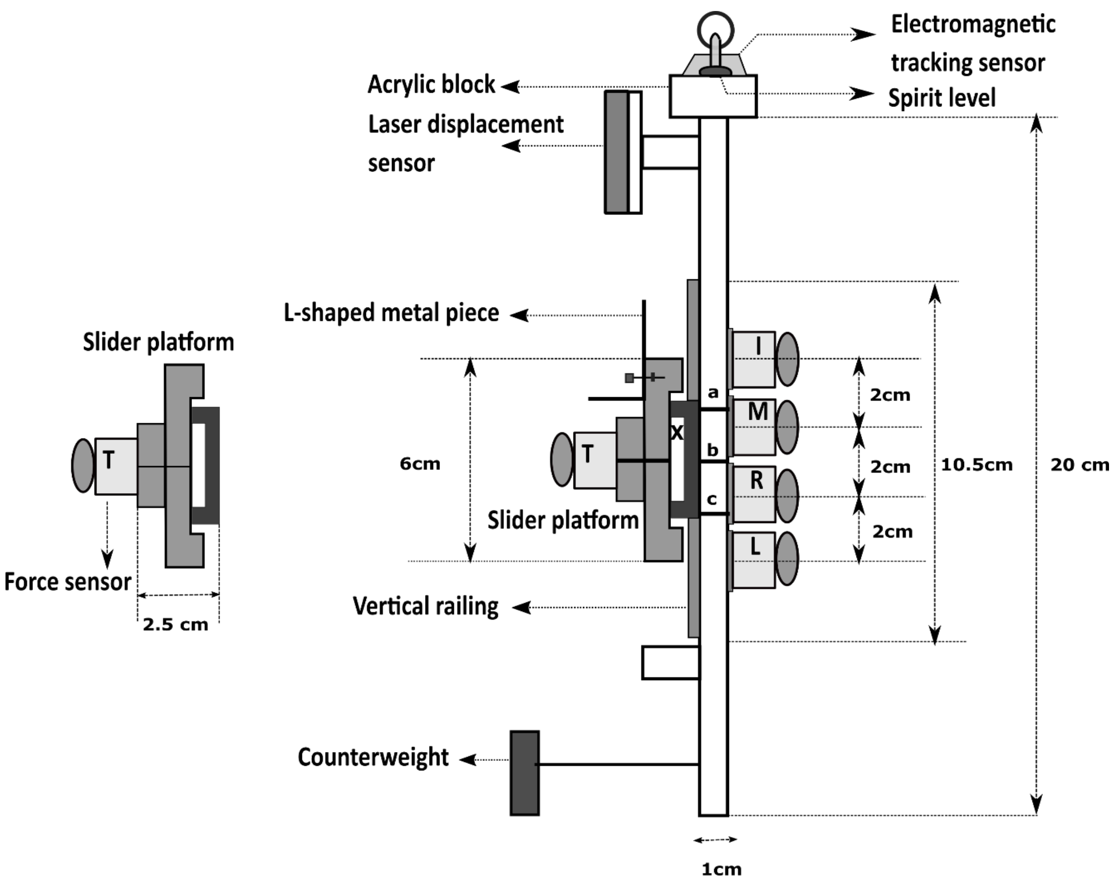

Figure 5.2 Schematic diagram of the five-finger grasping handle. The dimensions of the aluminium handle frame is (20 x 1 x 3) cm. An acrylic block (1.3 x 3 x

8) cm is mounted on top of the frame in the anterior-posterior direction to place the spirit level and the electromagnetic tracking sensor. The slider platform (6 x 2.5 x 3) cm with mass of 0.101kg was shown separately. A rectangular aluminum counterweight (2.5 x 1 x 5) cm of mass 0.035kg was placed close to the bottom of the handle to shift the center of mass of the handle close to the geometric center of the handle (represented with symbol 'X'). The grip aperture of the handle is 6.5cm. The surface of the force sensors were covered with 100 grit sandpaper. The three horizontal lines (a, b, c) marked on the handle frame refers to the static positions (TOP, HOME and BOTTOM) of the slider platform. During trapezoid condition, the horizontal line b acts as HOME-TOP position (i.e position of the thumb at HOME when it is reached from the TOP). Similarly, the same horizontal line b acts as HOME-BOTTOM position (i.e position of the thumb at HOME when it is reached from the BOTTOM) during the inverted trapezoid condition. I, M, R, L, and T indicates index, middle, ring, little and thumb.

A laser displacement sensor (resolution: 5μm; OADM 12U6460, Baumer, India) was attached on top of the handle towards thumb side to measure the vertical displacement of the thumb platform. Towards the participant side, a spirit level with a bull's eye was provided. On the other side, an electromagnetic tracking sensor (Resolution 1.27 microns, Model: Liberty Standard sensor, Polhemus Inc., USA) was fitted to measure the position and orientation of the handle with reference to the source. The force/torque (thirty channels) and displacement data (single channel) were synchronized with six channels of digital data from the electromagnetic tracker using a customized LabVIEW program.

5.2.4 Experimental procedure

Participants were asked to wash their hands with soap and towel-dry before the commencement of the trials. They were required to sit comfortably with the forearm resting on the table-top as shown Figure 5.3(a). In order 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 table-top with velcro.

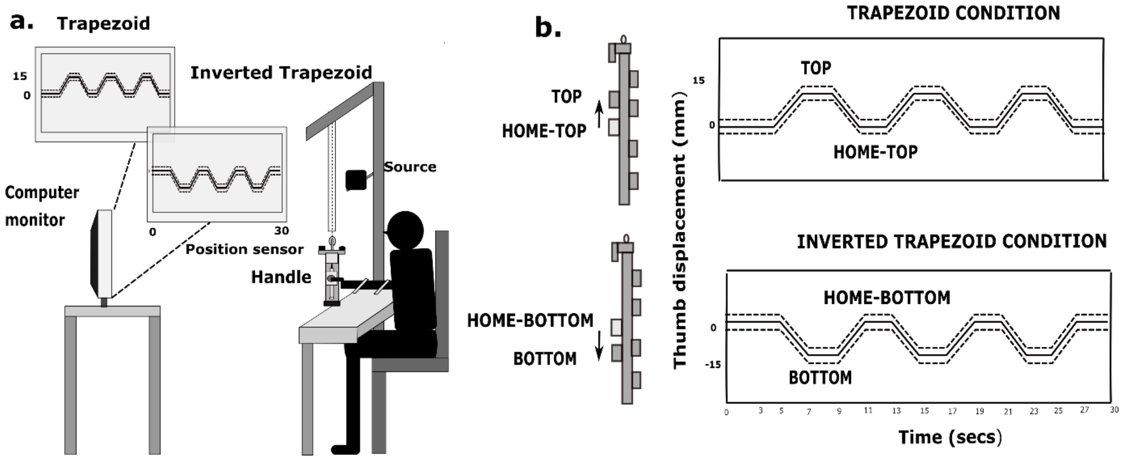

Figure 5.3 Schematic diagram of the experimental setup with participant holding the five finger prehensile handle with the thumb at four static positions. (a) A computer monitor with the trapezoid and inverted trapezoid patterns was shown to the participant at a distance of 1.5m away. The mass of the handle including the counterweight is 0.535 kg. The friction between the slider and railing was kept minimal by regularly cleaning and lubricating the ball bearing in the slider. In the trial belonging to trapezoid condition, three trapezoids (thick line) were shown consecutively, one after the other. Similarly, in the trial belonging to the inverted trapezoid condition, three inverted trapezoid patterns were shown. Error margins (dashed line) were shown for both the patterns. (b) Diagram showing the position of the thumb at four static positions: TOP, HOME-TOP, HOME-BOTTOM, BOTTOM. The static 'flat' portion traced by placing the thumb at the HOME position during trapezoid and inverted trapezoid conditions were called HOME-TOP and HOME-BOTTOM. The above diagram signifies the displacement of the thumb 1.5 cm above, from the HOME-TOP position (no shade) to the TOP position (grey shaded) during trapezoid condition. While in the inverted trapezoid condition, displacement of thumb 1.5 cm below, from the HOME-BOTTOM position (no shade) to the BOTTOM position (grey shaded). A single trial with 30 seconds trial duration on X-axis and 1.5 cm (or 15mm) thumb displacement on the Y-axis for both conditions is shown on the right panel

The experiment involved performing a task that consists of two different conditions: tracing trapezoid and inverted trapezoid patterns, as shown in Figure 5.3(b). A template pattern was displayed on the participant's computer monitor. At 0.5 cm above and below the pattern, dotted lines parallel to the pattern were shown. These dotted lines acted as acceptable error margins. The vertical displacement data of the thumb served as visual-feedback in real-time to trace the pattern displayed on the monitor. For the first five seconds of all the trials, the participants had to position the slider platform steady at the HOME position. This would then be followed by tracing the trapezoid or inverted trapezoid pattern depending on the condition.

In the trapezoid condition, the participants translated the slider platform vertically upwards for 1.5 cm from the HOME position. This involved tracing the "up-ramp" of a trapezoid pattern (i.e., ramp pattern traced by translating the slider platform upwards with constant velocity). At the new TOP position (reached at the end of every upward translation during trapezoid condition), participants need to hold the slider platform steady for 2s. This would trace the static 'flat' portion of the trapezoid pattern. This would then be followed by tracing the "down-ramp" of a trapezoid (i.e., ramp pattern traced by translating the slider platform downwards with constant velocity) that involved translating the thumb back to the HOME position. After reaching the HOME position, the participants had to hold the thumb platform steady at the HOME position for 2s, thereby tracing the static 'flat' portion at HOME. In each trial, the participants need to trace three such trapezoid patterns arranged sequentially.

Similarly, in the inverted trapezoid condition, the participants were made to trace the down-ramp of the inverted trapezoid pattern by translating the slider platform 1.5 cm downwards from the HOME position. At the new BOTTOM position (reached at the end of every downward translation during inverted trapezoid condition), participants need to hold the slider platform steady for 2s. This traced the static 'flat' portion of the inverted trapezoid pattern. This would then be followed by tracing the up-ramp of the inverted pattern. Thus, it involved translating the thumb back to the HOME position. Again, the participants had to hold the thumb platform steady at the HOME position for 2s, tracing the static ‘flat’ portion at HOME. In each trial, the participants need to trace three such inverted trapezoid patterns arranged sequentially. (see Figure 5.3(b)). In both conditions, in each trial, after tracing the last ramp, the participants had to hold the thumb platform steady at HOME position for 3s to complete the trial.

In each condition, there were twelve trials. The duration of each trial was 30 seconds. A minimum rest period of one minute was provided between the trials, and a ten minutes rest was provided between the conditions. The order of the conditions was balanced across participants.

5.3 Data Analysis

Data analysis was performed using Matlab (Version R2016b, MathWorks, USA). Force/Torque data and laser displacement data of thumb were lowpass filtered at 15Hz. There were four static ‘flat’ positions of the thumb: TOP and HOME-TOP during trapezoid condition, HOME-BOTTOM, and BOTTOM during inverted trapezoid condition (refer Figure 5.3(b)). In each trial of the two conditions, there were three static ‘flat’ portions for each position. The first one-second force data (of 100 samples) from each of these three static ‘flat’ portions were extracted. Therefore, in total, for a participant, there would be 36 segments (12 trials x 3 segments for each trial) of one-second data for each of the position.

5.3.1 Root Mean Square Error on the thumb displacement data

Thumb displacement data collected during both conditions were averaged across trials and participants. Root mean square error (RMSE) was computed for the four static positions (TOP, HOME-TOP, HOME-BOTTOM, BOTTOM) of the thumb displacement data with respect to the template pattern to examine the accuracy of thumb to trace the patterns. RMS error was calculated for each segment, then averaged across 36 segments for each participant, across all participants for each of the four static positions separately.

5.3.2 Absolute Normal and Tangential force

Normal and tangential forces of the individual fingers and thumb were averaged across 36 segments of all four static positions separately. Then, the normal and tangential force data were averaged across the time samples and participants. The standard error of the mean was also computed.

5.3.3 Change in the normal force

The *change* in the normal force gives information on the difference in the magnitude of forces produced before the start and after the end of each ramp. In each trial of each condition, there were three up-ramps and three down-ramps. In the trapezoid condition, 100 samples of force data immediately before the start of each up-ramp and immediately after the end of that up-ramp were averaged separately. The difference in the mean force was computed. There were 36 such differences (12 trials x 3) for a single participant. Likewise, the *change* in the normal forces of all the fingers and thumb were obtained for the down-ramps of trapezoid condition. Similarly, it was computed for both down-ramps and up-ramps of inverted trapezoid conditions separately. Finally, these data were averaged across all participants for various conditions.

5.3.4 Safety margin

Safety Margin is the amount of extra normal force applied above the minimally required normal force to avoid slipping. It was computed by using the equation (2.2) mentioned in the chapter 2. In this study, safety margin was averaged across the segments and time samples for all four static positions separately. Safety margin values were Z transformed using the below equation (5.1) with lower bound as -1 and upper bound as +1.

$$SM_z = 0.5 * ln\left(\frac{1+SM}{1-SM}\right) \tag{5.1}$$

5.3.5 Statistics

Statistical analysis was done using R. Two two-way repeated-measures ANOVA was performed on the absolute normal and tangential forces with factors such as static position (levels: TOP, HOME-TOP, HOME-BOTTOM, BOTTOM) and fingers (levels: Index, Middle, Ring, Little). Another two-way repeated-measures ANOVA was performed on the *change* in the normal force with the factors as movements (levels: UP from HOME and DOWN from HOME) and fingers (levels: Index, Middle, Ring, Little). Sphericity test was done on the data, and the number of degrees of freedom was adjusted by Huynh-Feldt (H-F) criterion wherever required. Pairwise post hoc Tukey tests were performed to examine the significance within factors. Two one-way repeated-measures ANOVA was performed on Thumb normal force and thumb displacement data with factor as static position. Since, by mechanics, the thumb normal force is always relied on the normal forces of other individual fingers, ANOVA was performed separately for thumb normal force. Another two-way repeated measures ANOVA was performed on the Fisher's Z transformed Safety margin values with the factors such as fingers (level: Index, middle, ring, little, thumb) and static position (level: Top, Home Top, Home Bottom, Bottom). An equivalence test was performed to check for equivalence between the Thumb normal force at TOP and HOME-TOP static position using the two one-sided t-tests (TOST) approach[59] for a desired statistical power of 95%. The smallest effect size of interest (SESOI) was chosen as equivalence bounds.

5.4 Results

5.4.1 Task performance

Participants were able to trace the trapezoid and inverted trapezoid patterns within the error margin displayed on the template. Throughout the trial, during both conditions, participants maintained the handle in static equilibrium without any visible oscillations in the thumb displacement data. Furthermore, it was observed that the RMS error for the static positions in the inverted trapezoid condition (HOME-BOTTOM: Mean=6.20, SD=0.12; BOTTOM: Mean=18.49, SD=0.33) was significantly ($p<0.001$) greater than the static positions at the trapezoid condition (HOME-TOP: Mean=5.61, SD=0.24; TOP: Mean=7.14, SD=0.19). Thus, in Figure 5.4(b), a comparatively greater standard error of the mean for the thumb displacement data during the inverted trapezoid condition than during the trapezoid condition was seen. The average tilt angles measured at the four static positions was 1.72±0.38°

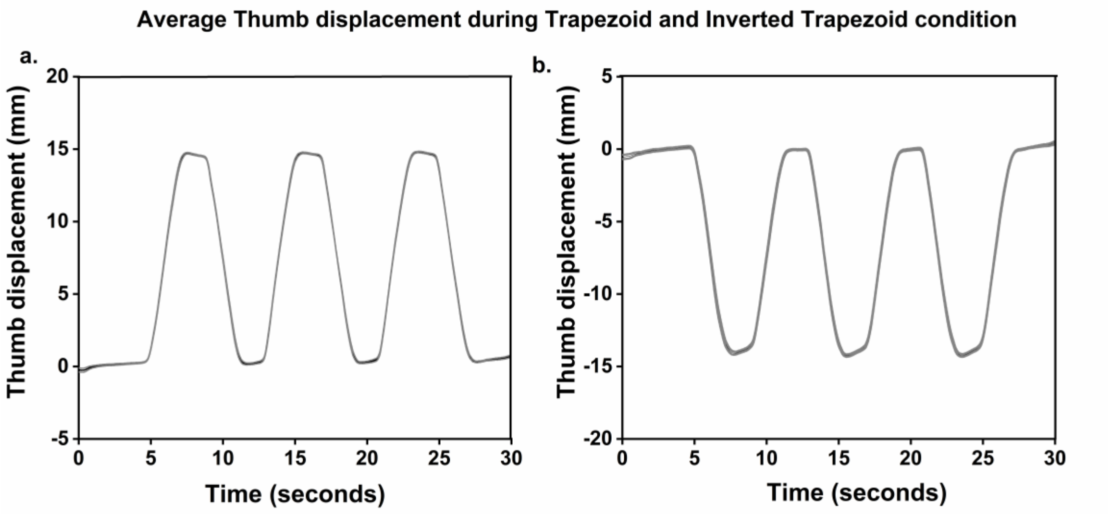

Figure 5.4 Average time profile of the thumb displacement during trapezoid and inverted trapezoid conditions with the standard error of the mean. The thumb displacement data shown here are averages across trials and subjects in each condition. (a) Average thumb displacement during trapezoid condition. (b) Average thumb displacement during inverted trapezoid condition. Normal and Tangential forces of fingers and thumb at four static positions

A two-way repeated-measures ANOVA on the normal forces of the individual fingers (except thumb) with the factors fingers and static positions showed a statistically effect of fingers ($F_{(3.63,39.93)}$= 40.34; $p<0.001$, $\eta^2_p=0.78$) corresponding to a significantly higher ($p<0.001$) normal force for the little finger followed by the ring finger compared to the radial fingers. There was a statistical main effect of the static position ($F_{(2.61,28.71)}$= 32.64; $p<0.001$, $\eta^2_p=0.74$) corresponding to a significantly higher normal force ($p<0.001$) when the thumb was at the BOTTOM position.

The interaction effect of the fingers x static positions was significant ($F_{(4.27,47.02)}$= 187.681; $p<0.001$, $\eta^2_p=0.94$), reflecting the fact that the absolute grip force of the small finger when the thumb was at the BOTTOM (7.25N) was statistically greater ($p < 0.001$) than the index finger normal force when the thumb was at the TOP (3.51N) as shown in Figure 5.5. Among central fingers, the ring finger (3.02N), showed significantly greater ($p<0.01$) normal force when the thumb remained at the BOTTOM than the middle finger (1.96N) when the thumb reached the TOP.

The normal force of the index finger (3.51N) was significantly higher ($p<0.001$) than the normal force of the middle finger (1.96N) when the thumb platform was held steady at the TOP. When the thumb reached the HOME position from the TOP during trapezoid condition, index finger normal force (Mean=1.64N, SD=0.54) was not statistically different ($t(11) = -1.072$, $p = 0.307$, $d_z=0.30$) from the middle finger normal force (Mean=1.79N, SD=0.57). Thus, the comparison was found to be statistically equivalent ($t(11) = 2.530$, $p = 0.014$) as the observed effect size of the dependent means fall within the equivalence bounds of $\Delta_L=-1.04$ and $\Delta_U=1.04$.

In the inverted trapezoid condition, while the thumb was tracing the BOTTOM of the inverted trapezoid, little finger normal force (7.25N) was found to be significantly greater ($p<0.001$) than the ring finger normal force (3.02N). Whereas, when the thumb reached the HOME position from the BOTTOM during inverted trapezoid condition, normal forces of the ulnar fingers were found to be statistically non-significant ($t(11) = 0.559$, $p = 0.588$, $d_z=0.16$). The TOST procedure on the dependent pairs (Ring: Mean=2.90N, SD=0.55, Little: Mean=2.78N, SD=0.43) confirmed that they were statistically equivalent with the observed effect size ($d_z = 0.16$) that was within the equivalence bounds of $\Delta_L=-1.04$ and $\Delta_U=1.04$.

Moreover, pairwise Post hoc Tukey tests confirmed that the little (2.78N) & ring (2.90N) fingers normal forces during inverted trapezoid condition were significantly greater than the middle finger normal force (1.86N, little: $p<0.05$, ring: $p<0.01$) when the thumb reached the HOME position from the BOTTOM. Similarly, the ulnar fingers normal forces (while the thumb was at HOME-BOTTOM) were statistically greater than the index (1.64N, ring: $p < 0.001$, little: $p < 0.001$) & middle fingers (1.79N, ring: $p<0.01$, little: $p<0.01$) normal forces when the thumb was at HOME-TOP position. Whereas, during the trapezoid condition, when the thumb reached the HOME position, little finger (3.43N) normal force was statistically greater ($p<0.001$) than the index (1.64N) and middle fingers (1.79N) normal forces.

One-way repeated-measures ANOVA on the thumb normal force showed a statistical effect of static position ($F_{(2.64,29.04)} = 31.90$; $p < 0.001$, $\eta^2_p = 0.74$). The thumb normal force at the TOP was not statistically different from the thumb normal force at HOME-TOP. Further, it was confirmed that the thumb normal force at the BOTTOM (12.13N) was significantly ($p<0.001$) greater than the thumb normal force at the HOME-TOP (9.58N) during trapezoid and HOME-BOTTOM (9.79N) during inverted trapezoid condition.

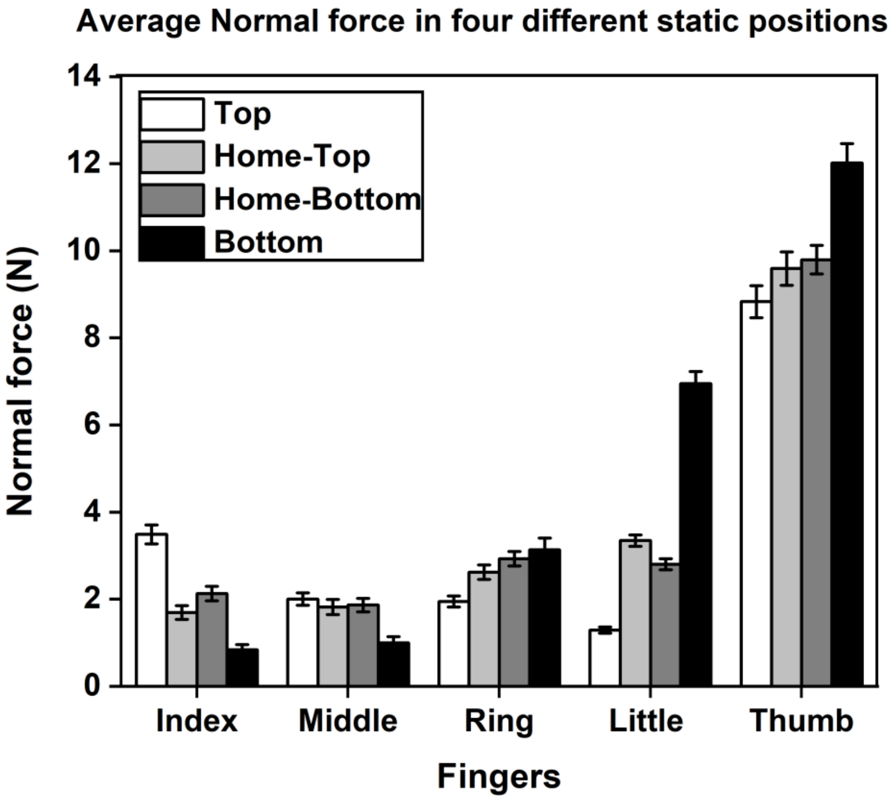

Figure 5.5 Average normal force of all the fingers with the standard error of the mean when the thumb was in four different static positions. The normal force of the little finger when the thumb was held at the BOTTOM position (black) was significantly greater ($p<0.001$) than the normal force of the index finger when the thumb was held at the TOP position (white). The index finger exerted significantly greater ($p<0.001$) normal force than the middle finger when the thumb was at the TOP position. Likewise, the little finger also exerted significantly greater ($p<0.001$) normal force than the ring finger when the thumb remained at the static BOTTOM position. Thumb normal force at the BOTTOM position was significantly greater ($p<0.001$) than the thumb normal force at static TOP, HOME-TOP (light grey), and HOME-BOTTOM (dark grey) positions.

With regard to the tangential forces, a two way repeated measures ANOVA showed that the factors such as fingers ($F_{(2.91,32.01)}= 7.50$; $p<0.001$, $\eta^2_p=0.40$), static positions ($F_{(2.1,23.1)}= 9.65$; $p<0.001$, $\eta^2_p=0.46$) and fingers X static positions ($F_{(4.23,46.53)}= 38.15$; $p<0.001$, $\eta^2_p=0.77$) interaction affected significantly the tangential forces of the individual fingers (except thumb). When the thumb was at TOP and HOME-TOP during the trapezoid condition, the index finger tangential force was neither significantly different nor statistically equivalent to the middle finger tangential force. When the thumb was at the BOTTOM, the little finger tangential force (2.66N) was significantly greater ($p < 0.001$) than the ring finger tangential force (1.13N) (refer Figure 5.6).

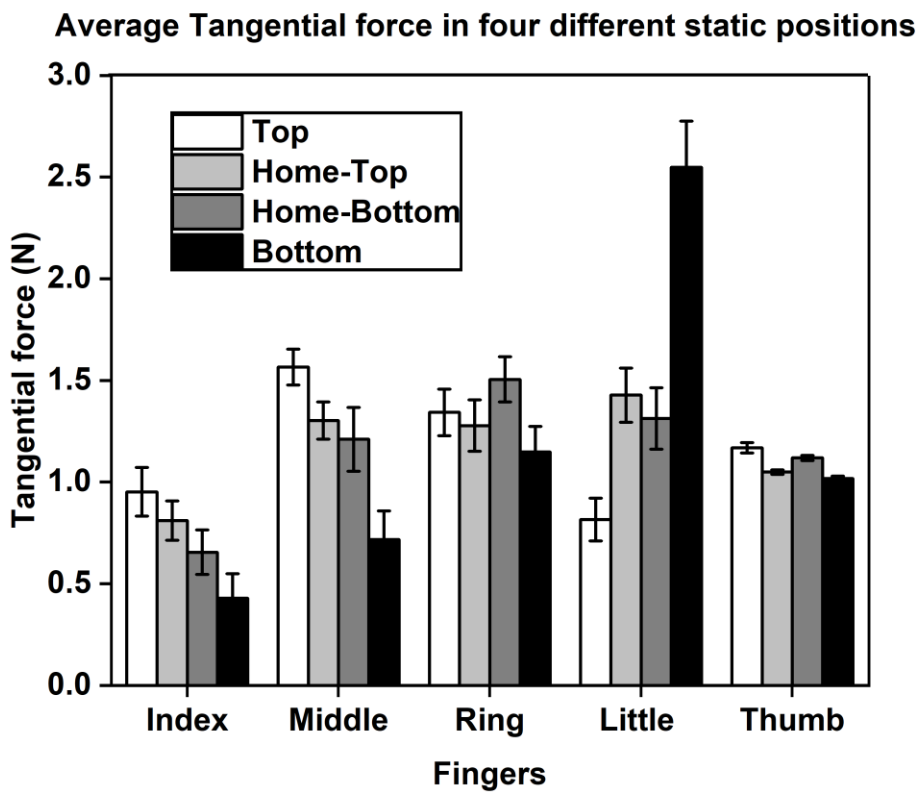

Figure 5.6 Average tangential force of all the fingers when the thumb was at four different static destinations. The little finger tangential force at static BOTTOM destination was found to be significantly greater ($p<0.001$) than the index finger tangential force when the thumb remained at static TOP destination.

Whereas when the thumb returned to the HOME-BOTTOM, ulnar fingers tangential forces (Ring=1.50N, SD=0.37; Little=1.31N, SD=0.49) remained statistically equivalent, with the observed effect size (d_z=0.30), lying within the equivalence bounds of Δ_L=-1.04 and Δ_U=1.04. At the same position, ulnar fingers tangential forces were found to be significantly greater ($p < 0.05$) than the index finger tangential force (0.62N).

Notably, the little finger tangential force (2.66N) (when the thumb was at static BOTTOM position) was significantly greater ($p<0.001$) than the index finger tangential force (0.92N) (when the thumb was at static TOP position) and both radial fingers (Index: Mean=0.43N, Middle: Mean=0.70N) (when the thumb remained at BOTTOM).

5.4.2 Change in the normal forces of the individual fingers

From the results of the two-way repeated-measures ANOVA on the *change* in the normal forces of the individual fingers (see Fig.4.7), a significant main effect of factors such as fingers ($F_{(2.34, 25.74)}$= 78.104; $p<0.001$, η^2_p=0.87), movements ($F_{(0.83, 9.13)}$= 49.83; $p < 0.001$, η^2_p= 0.81) and their interaction ($F_{(2.49, 27.39)}$= 301.63; $p<0.001$, η^2_p=0.96) was observed.

During the upward translation of the thumb from HOME, the *change* in the grip force of the index finger (1.79N) was significantly different ($p < 0.001$) from the *change* in the grip forces of the middle (0.008N), ring (-0.88N) and little (-1.84N) fingers. Likewise, during the downward translation of the thumb from HOME, the *change* in the normal force of the little finger (4.01N) was significantly greater ($p<0.001$) than the *change* in the normal force of the index (-1.07N), middle (-0.93N) and ring (-0.03N) fingers.

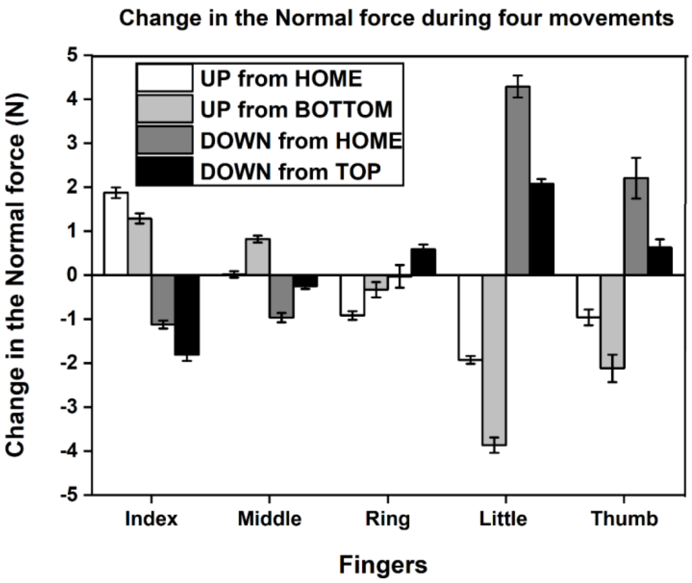

Figure 5.7 Average change in the normal force with the standard error of the mean during four movements of the thumb. The change in the normal force of all fingers and thumb obtained from the up-ramp of the trapezoid condition fall into the category UP from HOME position. In the same way, change in the normal force obtained from the down-ramps of trapezoid condition, up-ramps, and down-ramps of inverted trapezoid condition fall into categories such as DOWN from TOP position, UP from BOTTOM position, and DOWN from HOME position, respectively. The change in the normal force of the little finger during the downward movement of thumb from HOME (DOWN from HOME- dark grey) was significantly greater ($p<0.001$) than the change in the normal force of the index finger during the upward movement of thumb from HOME (UP from HOME- white).

Since the magnitude of the thumb displacement remained the same in both directions (also, the fingers were equidistant from the center of the handle), the increase in the peripheral fingers normal force was expected to be the same. However, the critical finding was that the *change* in the normal force of the small finger (4.01N) (when the thumb moved down from HOME) was significantly greater ($p<0.001$) than the *change* in the grip force of the index finger (1.79N) (when the thumb moved up from home)(see Figure 5.7). Table 5.1 summarizes the salient results with the ANOVA details.

Table 5.1 Summary of results with the ANOVA details. The table shows the main result obtained from the statistical analysis (ANOVA) for the outcome variables such as Absolute Normal force, Absolute Tangential force, Change in the Normal force and Thumb Normal force with the significance level.

OUTCOME VARIABLE	**ANOVA**	**FACTORS AND LEVELS**	**MAIN RESULT**	**SIGNIFICANCE**
Absolute Normal force (NF)	Two-way repeated measures ANOVA	**Factor 1: *Fingers*** Levels: Index, Middle, Ring, Little **Factor 2: *Static positions*** Levels: TOP, HOME-TOP, HOME-BOTTOM, BOTTOM	Index finger NF (Thumb at TOP) < Little finger NF (Thumb at BOTTOM)	$p < 0.001$
Absolute Tangential force (TF)			Index finger TF (Thumb at TOP) < Little finger TF (Thumb at BOTTOM)	$p < 0.001$
Change in the Normal force			Change in the Index finger NF (Thumb at TOP) < Change in the Little finger NF (Thumb at BOTTOM)	$p < 0.001$
Thumb Normal force	One-way repeated measures ANOVA	**Factor 1: *Static positions*** Levels: TOP, HOME-TOP, HOME-	Thumb NF (Thumb at BOTTOM) > Thumb NF (Thumb at HOME-	$p < 0.001$

		BOTTOM, BOTTOM	BOTTOM) and Thumb NF (Thumb at HOME-TOP)	

5.4.3 Safety margin of the individual fingers

A two-way repeated measures ANOVA performed on the safety margin with factors such as fingers and position showed significant effect on both factors fingers ($F_{(4,44)}$ = 71.43; p<0.0001, η^2_p =0.86), position ($F_{(3,33)}$ = 5.04; p<0.001, η^2_p =0.31), and interaction ($F_{(12,132)}$ = 23.83; p<0.0001, η^2_p=0.68). Though the forces of little finger were significantly greater than the ring finger when the thumb was held at BOTTOM position, safety margin of the ring and little finger was not significantly different (refer Figure 5.8). Therefore, by means of TOST procedure, it was confirmed that the dependent pair (Ring: Mean= 0.74, SD=0.21; Little: Mean=0.78, SD=0.18) would be statistically equivalent (t(11) = 3.018, p = 0.00585) when the thumb is held at BOTTOM position as their observed effect size falls within the equivalence bounds of Δ_L=-1.04 and Δ_U=1.04.

Whereas when the thumb was held at the TOP position, index finger safety margin (Mean=0.96, SD=0.31) was significantly (p<0.0001) greater than middle finger safety margin (Mean=0.21, SD=0.14). Apart from this, index finger safety margin when the thumb was at TOP position (Mean=0.96, SD= 0.31) was statistically equivalent (t(22) = -1.861, p = 0.0381) to the little finger safety margin (Mean=0.78, SD= 0.18) when the thumb was held at the BOTTOM position as the observed effect size of the independent mean pair falls within the equivalence bounds of Δ_L=-1.47 and Δ_U=1.47.

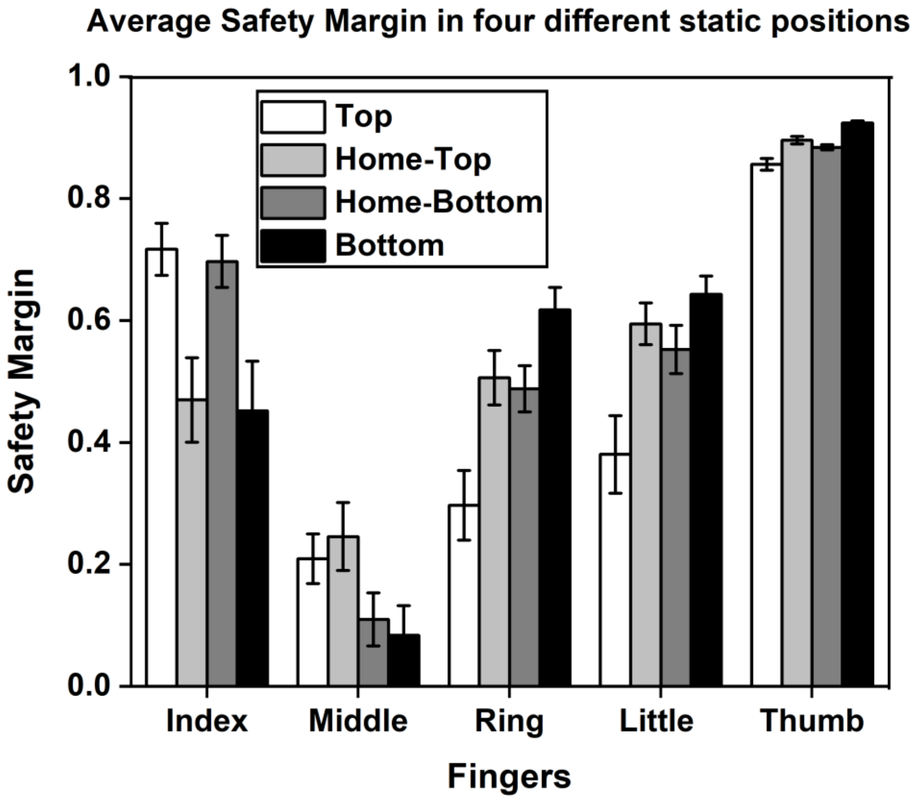

Figure 5.8 Average Safety Margin of the individual fingers and thumb with the standard error of the mean. The safety margin of the ring and little fingers was found to statistically equivalent when the thumb was held at BOTTOM position. However, safety margin of the index finger was significantly ($p<0.0001$) greater than the safety margin of the middle finger when the thumb was held at the TOP position.

5.5 Discussion

In this study, the contribution of peripheral fingers towards handle stabilization when the thumb platform was vertically translated to different positions was investigated. The displacement data of the thumb while tracing the pattern displayed on the monitor served as visual feedback for the participants. The participants were instructed to maintain the static equilibrium of the handle throughout the trial. Since, the thumb platform was displaced to a level above and below the centers of the central finger sensors from the HOME position, with reference to the results of the grasping study, it was posited that the role of index and little fingers in establishing static equilibrium would be similar. However, in contradiction to this expectation, fingertip forces of the peripheral fingers showed different behavior during handle stabilization.

One distinguishing feature of this study was how torque changes were introduced to the grasped handle. Few studies introduced torque changes by having thumb position fixed to discrete locations [24], [45]. While some studies [30], [32], [34] focused on examining the fingertip forces in handle stabilization when a specific mass was suspended at a certain distance on a horizontal bar fitted to the base of the handle. This induced external torque changes to the grasped handle, which could ultimately lead to the rotation of the handle. The novelty of the current study is placing the thumb on a slider platform and vertically translating over the railing provided at the handle. The upward and downward translation of the thumb towards and away from the HOME position cause a continuous change in the moment arm of the thumb normal force. Hence, the translation of the movable thumb platform introduced torque changes to the handle.

Also, in previous studies, the external torque changes were of the order of newton-meters (Nm). Therefore, there was a necessity to produce a large compensatory moment to counter-balance. In the current study, the magnitude of thumb displacement was 1.5 cm in either direction. Hence, the magnitude of torque changes was of the order of newton-centimeters (Ncm), which was comparatively lesser than the previous studies. Whether the peripheral fingers behave similarly as in the earlier studies, supporting the

MAH during small torque changes is worthy of exploration. Apart from this, the handle utilized in the current study required a movement at Carpometacarpal (CMC) joint of thumb for task execution (i.e., torque changes).

During the trapezoid condition, when the thumb platform reached the TOP position, the index finger produced a greater normal force than the middle finger. Similarly, when the thumb reached the BOTTOM position during the inverted trapezoid condition, the little finger produced a greater grip force than the ring finger. Although the thumb motion caused a rise in the grip force of both the peripheral fingers, further investigation was done to examine how these finger forces showed significant variation in detail. As mentioned in the introduction, there were four possible options by which the peripheral fingers normal force pattern may vary (refer Figure 5.1).

According to the first and fourth option, the index finger would show a greater *change* in the normal force when the thumb platform translates from HOME to TOP position than the little finger when the thumb platform translates from HOME to BOTTOM position. As the index finger is stronger than the little finger [17], [26], [50], the *change* in the index finger normal force was expected to be greater than the *change* in the little finger normal force. The only difference is that, absolute normal force of the peripheral fingers when the thumb is held at TOP and BOTTOM could either be comparable (first option) or the absolute grip force of the index finger could be significantly greater than the little finger (fourth option).

Based on the second option, the *change* in the normal force of peripheral fingers is expected to be equivalent. However, in reality, the result was matching the pattern expected in the third option. According to the third option, the *change* in the normal force and the absolute normal force will be significantly greater for the small finger than the index finger. What could be the reason for the larger increase seen in a weaker finger (little) when compared with a stronger finger (index)? Considering the displacement of the two fingers is the same, this behavior of the little finger is intriguing. This was the principal question that was focussed in this chapter of the thesis.

While tracing the up-ramp of the trapezoid pattern, there was an increase in the clockwise moment due to the increase in the moment arm for the grip force of the thumb. Consequently, an anticlockwise moment was exerted by increasing the grip force of the radial fingers. In an earlier study [24], the grip force sharing pattern of the individual fingers (except thumb) varied while the location of the thumb was changed discretely. The normal force of the radial finger increased when the thumb was positioned opposite to the middle finger. The results of current study are also same as these results. Since the ring and little fingers produce a clockwise moment, the grip force of the ring (around 1N) and little finger (around 2N) decreased during the up-ramp of the trapezoid.

Furthermore, the tangential force of the thumb increased slightly (around 0.10N) during the upward translation of the thumb from the HOME position due to the contribution of inertial force along with the gravitational force [47], [89]. The rise in the load force of the thumb has to be counteracted by a corresponding decrease in the load force of the virtual finger (VF). Among the VF, the drop in the tangential force could have been evenly shared within all the fingers or with ulnar fingers alone. Instead, a notable drop in the tangential force was seen only in the little finger. The reason for the little finger to decrease its tangential force during the upward translation of the thumb may be explained from a biomechanics perspective. The upward movement of the thumb while holding an object is considered as an extension movement or radial abduction of thumb's CMC joint. This movement happens due to the contraction of muscles such as abductor pollicis longus and extensor pollicis brevis[65].

Abductor pollicis longus, a primary radial deviator of the wrist, contracts causing radial deviation of the wrist joint[90]. Hence, it was believed that the radial deviation caused by the radial abduction of the thumb could be resisted by a possible contraction of the abductor digiti minimi of the little finger as it could cause ulnar deviation of the wrist joint[67]. In addition to the anatomical restriction of the wrist motion, externally, the participant's wrist was strapped by using velcro to arrest any unwanted movement of the wrist. Thus, it was believed that the radial abduction of the thumb while grasping a handle may have resulted in the little finger abduction in the form of medial rotation. Abduction of the little finger was indirectly noticeable from the decrease in the little finger tangential force. Consequently, tangential and grip forces of the index, middle, and ring fingers increased slightly.

During the downward translation of the thumb during both conditions, the load force of the thumb dropped slightly by about 0.2N. Subsequently, the load force of the other fingers increased to maintain the vertical equilibrium. From the mechanics standpoint, if there were a rise in the load force of the radial fingers, it would be attended by the rise in grip force of same finger to prevent slip[91]. Thus, it would cause a tilt in the anticlockwise direction, adding up to the tilt caused due to the downward shift of the thumb to the BOTTOM position. The increase in the tangential force could have been shared by the ulnar fingers. But, in reality, there was a significant rise in the tangential force of only the small finger, while the ring finger showed a drop in the tangential force. This was contrary to the expectations. Since the *change* in the forces exerted by the little finger was quite prominent, the forces exerted by the other fingers reduced.

The downward translation of the thumb towards the little finger may be considered a full flexion or opposition movement[65]. Opponens pollicis of the thumb is responsible for this movement. It contracts during the downward translation of the thumb to BOTTOM position. Meanwhile, opponens digiti minimi of small finger acts in synergy with the opponens pollicis longus[92]. It is known that the opponens digiti minimi is one of the antagonist muscles of the opponens pollicis. Thus, there is a possibility for the little finger to produce lateral rotation, which occurs in the form of upward movement of the point of force application (or finger ‘rolling’ within the sensor) of the little finger towards the ring finger. This could have caused a rise in the little finger’s load force while the other fingers load force dropped to maintain the vertical equilibrium.

Subsequently, the rise in the load force of the small finger would be followed by rise in the grip force of same finger. Thus, the full flexion (downward translation of the thumb from HOME position) of the thumb’s CMC joint may have caused simultaneous adduction of the little finger (i.e., the movement of the little finger towards the ring finger side). This is indirectly apparent from the tangential forces. Conversely, such a rise in the index finger tangential force was not seen when the thumb translated to the TOP position. The radial abduction of the thumb did not cause a considerable amount of abduction of the index finger, as both the grip and load forces of the adjacent middle finger contributed towards exerting a pronation moment. So, the involvement of the index finger tangential force was slightly less in the total load force.

Thus, the downward movement of the thumb caused a substantial increase in the adduction of the little finger, probably due to morphological reasons. A significantly greater grip force was exerted by the little finger during the supination moment than the index finger during the pronation moment. Consequently, due to the higher increase in the little finger normal force, thumb normal force increased to 12N during the downward translation to compensate for the clockwise tilt caused. In the case of upward translation of thumb from HOME to the TOP position, thumb normal force was 8N because the *change* in the index finger normal force was not high enough. Thus, the little finger forces are different from index finger forces during the thumb movement towards them. Further investigation on the anatomical relationship between the thumb and little finger is necessary to better understand this distinct behavior of the little finger.

5.6 Conclusion

When an unsteady thumb platform translated to different positions vertically, the normal forces exerted by the individual fingers varied in a systematic way. In particular, if the thumb platform remained static at various positions, it caused remarkable changes in the forces of peripheral fingers for object stabilization. The forces and *change* in the force by the small finger when thumb was at the BOTTOM position were comparatively greater than those of the index finger when the thumb was at the TOP position. This distinct behavior of the little finger compared to the other fingers perhaps suggests that there is an anatomical/morphological relationship between the thumb and little finger. Further investigation on the anatomical function during the task performance may give a better idea of this relationship.

CHAPTER 6.

SUMMARY OF THE THESIS AND FUTURE DIRECTION

6.1 Summary of the thesis

Stabilization in hand-held object can be attained by maintaining the object in static equilibrium. Although the percentage of normal force shared by the individual fingers and thumb varied while grasping a rectangular handle, the little finger exerted comparatively lesser normal force than others. Various reasons exist, such as the structural aspect of the little finger, anatomical location, and biomechanical constraint, that may restrict its performance.

Some studies performed in the past required the production of supination torque to establish object stabilization when an external torque was introduced to the grasped object in the pronation direction. In such supination torque requirement tasks, the mechanical advantage hypothesis was tested to examine the contribution of peripheral fingers. In the current research, rather than introducing external torque by suspending load at a distance from the center of mass, torque changes were introduced to the handle by placing the thumb on a slider platform. Thus, the contribution of the thumb to support the load of the grasped object was reduced. This resulted in inducing a pronation torque to the grasped object. However, the instruction was to maintain the handle at static equilibrium. Therefore, to overcome the pronation torque caused due to the drop in the tangential force of the thumb, a compensatory supination torque was required to be produced by the ulnar finger normal forces. Since the “little finger has a longer moment arm" than the ring finger, it was expected to produce greater normal force to establish object stabilization and obey the mechanical advantage hypothesis.

In contrast to the expectation, during the free condition, when the unsteady thumb platform was held between the central fingers, ring, and little fingers normal forces increased and were found to be comparable to overcome the drop in the load contribution of the thumb. Consequently, there emerged a question of whether ulnar fingers would obey the mechanical advantage hypothesis when the mass of the handle was systematically increased by adding external loads of different masses. As the contribution of the thumb tangential force in producing supination moment was restricted to 1N (mass of the slider or unsteady platform=0.100kg), normal forces of ulnar fingers were required to produce compensatory supination moment. Between the ulnar fingers, in support of the mechanical advantage hypothesis, the expectation was that the little finger would share greater normal force than the ring finger when there is a need for a greater compensatory supination torque due to the systematic increase in the mass of the grasping handle.

Results of some of the previous studies on multi-finger grasping supported the mechanical advantage hypothesis, while the results of a few other studies only partially supported the hypothesis. According to the finger coordination study on mechanically fixed object [29], it was assumed that the applicability of the mechanical advantage hypothesis is task and effector-specific. Since there were no details available on what kind of task lend support to this hypothesis, the second study was carried out to explore if MAH would be supported when the mass of the handle was increased systematically. Also, to examine if MAH is task-specific and determine the kind of task that supports the hypothesis. Therefore, in the second study, external loads of masses 0.150kg, 0.250kg, 0.350kg, and 0.450kg were systematically added at the bottom (i.e, below the center of mass of the handle). According to a multi-finger prehension study[36], an external load of the same mass (0.150kg) was suspended at a distance, causing a supination moment (0.14Nm) less than the moment required for the second study found to have results corroborating the mechanical advantage hypothesis. Therefore, it was suspected that with an addition of 0.150kg of load, resulting in the need for the supination moment of 0.22Nm, the hypothesis would be supported.

In contrast to the expectation, ulnar fingers produced comparable normal forces for the loads such as 0.150kg, 0.250kg, and 0.350kg. The mechanical advantage hypothesis was supported only for the addition of 0.450kg of load. This behavior of the ulnar fingers confirms that the support for MAH is specific to a particular task. As the nature of the task varies, support to MAH also varies. Though the mass of the handle was increased systematically by adding external loads of different mass, the mechanical advantage hypothesis was supported only for the external load of 0.450kg. It was quite difficult to establish static equilibrium when a load of 0.450kg was suspended to the handle that already had a constraint of minimal tangential force contribution by the thumb. Due to the heavy mass suspension, in order to avoid (or reduce) the strain caused by producing greater grip forces together by ulnar fingers, the system might have preferred to make use of any one of the fingers among the ulnar fingers. Since the little finger has the mechanical advantage (of longer moment arm), the system might have preferred to choose little finger, so as to reduce the total effort or force produced by ulnar fingers without compromising to produce required magnitude of supination torque[77]. Thus, little finger would have produced greater normal force than the ring finger.

In order to confirm that a task difficulty induces to obey MAH, a separate grasp task was designed using the handle with a slider platform. The task was made uncomfortable by imposing restrictions to produce a minimal target normal force by the thumb, in addition to the limitation of producing a minimal tangential force by mounting over the slider platform. Since the handle had to be maintained in static equilibrium in the presence of the constraints imposed on thumb's tangential force, normal force, and position, the task was quite challenging to complete. Due to the restriction to produce lesser normal force by the thumb, forces of other fingers would have reduced. Therefore, it would have caused a drop in the supination torque due to the decrease in the ulnar finger normal forces. Consequently, there might be a pronation torque in the anti-clockwise direction. Thus, there arose a requirement of producing minimal normal force by the ulnar fingers, but, sufficient supination torque by the same fingers. From a mechanics perspective, obeying mechanical advantage principle would be a suitable option. In addition to the mechanical advantage of the little finger, it also has an anatomical advantage of an additional group of intrinsic muscles compared to the ring finger for the dexterous control of its forces. Therefore, it was believed that it could also be due to that, mechanical advantage principle might have been supported in the uncomfortable grasp study. Thus, it was believed that the difficulty experienced to maintain the handle in static equilibrium while producing lesser normal force by the thumb had induced to support the mechanical advantage hypothesis.

A pattern tracing study was conducted to examine the contributions of peripheral fingers when the thumb platform was translated in the vertical direction while grasping the handle. Based on a multi-finger study[24], when the thumb was held at the level above and below the center of the middle and ring finger sensor, the change in the percentage of peripheral finger grip forces was comparable. Therefore, it was expected that the *change* in grip force of peripheral fingers would be same when the thumb was shifted to the level above and below the middle and ring finger sensor center. On the contrary, the change was significantly greater for the little finger than the index finger. The little finger showed a drop in the tangential force, while the remaining fingers showed a rise in the tangential force when the thumb platform moved upward. Similarly, when the thumb platform was moving downward, the little finger showed a rise in the load force while the remaining fingers showed a drop in the tangential force. The result shows that the little finger behaves completely different from the other fingers during the thumb translation. Thus, fingertip force data of the individual fingers conveys a biomechanical relationship between the thumb and little finger. Although the little finger has a smaller structure than other fingers, the biomechanical and neural inter-relationship between the little finger and thumb served to act as a source for such a marked behavior of the little finger compared to the index finger.

In addition to this result on the peripheral finger contribution, it was suspected that the small finger would exert statistically higher normal force compared to the ring finger when the thumb platform was translated downwards from the home position. As per the expectation, the mechanical advantage hypothesis was supported. Since CMC joint of thumb possesses restricted motion during the downward translation of the thumb towards the little finger, maintaining the handle equilibrium became quite challenging.

Hence, it was believed that system would have chosen to make use of the mechanical advantage of small finger to minimize the total effort of the ulnar fingers and complete the task successfully during the difficult situation.

Therefore, this thesis focuses on the investigation of the ulnar fingers' contribution, especially little finger, in object stabilization when the contribution of the thumb in supporting the load of the grasped object was artificially reduced. The intricate details on the contribution of other fingers in object stabilization are out of this thesis's scope as they require further modifications to the design of the grasped object.

6.2 Limitation and future direction

1. Although it was found that the task difficulty or individual's ability of managing a task causes to prefer the use of the mechanical advantage of little finger, the level of difficulty experienced was not quantified in the current research. Therefore, a quantitative assessment of the difficulty associated with the task is necessary to be measured to predict the preference of the system well in advance.
2. Apart from this limitation, the studies performed in the current research were focused only on the analysis of fingertip forces data. However, in the future, the experiments can be repeated by including EMG and EEG acquisition systems. EMG gives information on the specific hand muscles activated during the task performance. While the EEG system provides details of the neural activity corresponding to the finger and thumb movement and helps identify brain regions corresponding to the particular action.

3. Further, recording the motor unit activity pattern from the portion of the flexor digitorum profundus, which is responsible for the flexion of ulnar fingers, helps better understand the underlying mechanism followed by the central nervous system in preferring little finger for various conditions.
4. Rather than increasing the ulnar fingers gripping force based on the instruction, the tasks involved in the current research provide the chance to increase the ring and little finger's normal forces voluntarily. Thus, a task-based activation of the ulnar fingers coupled with the interactive user interface helps the participants (which could be extended to patients) experience simplicity and enthusiasm during their rehabilitation process. Therefore, it relieves the stress and helps to recover faster. Hence, these studies performed with the current handle can be extended to evaluate the progress of recovery in patients.

APPENDIX A.

EQUIVALENT TEST

Two one-sided t-test (TOST t-test) approach

[1] TOST t-test is an equivalence test performed to examine whether the groups are statistically equivalent.

[2] The first step was to determine whether the groups were dependent or independent. The ring and little finger's normal forces during the free condition were tested to determine the statistical equivalence. They showed statistically insignificant results in the post hoc tukey comparison and thus tested for statistical equivalence. Since both the ring and little finger normal forces were collected during the same experimental ‘free’ condition (when the mechanical constraint was removed), the ring and little finger normal forces were assumed to be dependent groups.

[3] The formula for computing the equivalence bounds between the dependent groups is mentioned below.

$$\text{Equivalence bounds} = \frac{\left[\text{qnorm}(1-\alpha)+\text{qnorm}\left[1-\left(\frac{1-\text{power}}{2}\right)\right]\right]}{\sqrt{\text{n}}} \tag{A.1}$$

The above formula for equivalence bounds was derived from Chow et al. 2007

$$\boldsymbol{\delta} = \frac{(z_{\alpha/2}+z_{\beta})}{\sqrt{n}} \tag{A.2}$$

$$Equivalence\ bounds\ (dz) = \frac{[t_{0.95} + t_{0.975}]}{\sqrt{n}} \tag{A.3}$$

$$Equivalence\ bounds\ (dz) = \frac{[t]}{\sqrt{n}} \tag{A.4}$$

n=15, Alpha=0.05, Statistical power=0.95

Z score of $t_{0.95}$=1.64,

Z score of $t_{0.975}$ =1.96

d_z= 3.60/3.87= **0.931**

Thus, the lower and upper equivalence bounds were -0.93 and 0.93 for a desired statistical power of 0.95, a sample size of 15, and an alpha of 0.05.

[4] The computed equivalence bounds were verified in the R package by using the following function:

Command: powerTOSTpaired (alpha=0.05, N=15, statistical_power=0.95)

Response: The equivalence bounds to achieve 95% power with N = 15 are

Lower = -0.9307599 Upper=0.9307599

[5] The following function in the R package was used to test statistical equivalence.

Command: TOSTpaired(n=15,m1=2.69, m2=2.86,sd1=0.87,sd2=0.74,r12=-0.07,low_eqbound_dz=-0.93,high_eqbound_dz=0.93)

[6] The results exhibited that the grip force of the ulnar fingers were statistically equivalent during the simple grasp condition.

[7] Post hoc power analysis was performed to compute the statistical power with the data collected from the 15 participants. The statistical power of 100% was achieved with a sample size of 15.

REFERENCES

[1] R. B. Muir and R. N. Lemon, “Corticospinal neurons with a special role in precision grip,” *Brain Research*, vol. 261, no. 2, pp. 312–316, Feb. 1983, doi: 10.1016/0006-8993(83)90635-2.

[2] D. Pfaff, *Neuroscience in the 21st Century*. 2013. doi: 10.1007/978-1-4614-1997-6.

[3] B. E. Lung and B. Burns, “Anatomy, Shoulder and Upper Limb, Hand Flexor Digitorum Profundus Muscle,” in *StatPearls*, Treasure Island (FL): StatPearls Publishing, 2022. Accessed: Jan. 25, 2022. [Online]. Available: http://www.ncbi.nlm.nih.gov/books/NBK526046/

[4] E. Okwumabua, M. A. Sinkler, and B. Bordoni, “Anatomy, Shoulder and Upper Limb, Hand Muscles,” in *StatPearls*, Treasure Island (FL): StatPearls Publishing, 2022. Accessed: Jan. 25, 2022. [Online]. Available: http://www.ncbi.nlm.nih.gov/books/NBK537229/

[5] V. Nanayakkara, G. Cotugno, N. Vitzilaios, D. Venetsanos, T. Nanayakkara, and M. Sahinkaya, “The Role of Morphology of the Thumb in Anthropomorphic Grasping: A Review,” *Frontiers in Mechanical Engineering*, vol. 3, Jun. 2017, doi: 10.3389/fmech.2017.00005.

[6] A. Tang and M. Varacallo, “Anatomy, Shoulder and Upper Limb, Hand Carpal Bones,” in *StatPearls*, Treasure Island (FL): StatPearls Publishing, 2022. Accessed: Jan. 25, 2022. [Online]. Available: http://www.ncbi.nlm.nih.gov/books/NBK535382/

[7] T. B. Anderson and B. Bordoni, “Anatomy, Shoulder and Upper Limb, Forearm Nerves,” in *StatPearls*, Treasure Island (FL): StatPearls Publishing, 2022. Accessed: Jan. 25, 2022. [Online]. Available: http://www.ncbi.nlm.nih.gov/books/NBK554514/

[8] N. A. Bernshteĭn, *The co-ordination and regulation of movements*. Oxford; New York: Pergamon Press, 1967. Accessed: Jan. 08, 2021. [Online]. Available: http://books.google.com/books?id=F9dqAAAAMAAJ

[9] V. M. Zatsiorsky and M. L. Latash, “Multi-finger Prehension: An overview,” *J Mot Behav*, vol. 40, no. 5, pp. 446–476, Sep. 2008, doi: 10.3200/JMBR.40.5.446-476.

[10] J. R. Flanagan, M. K. O. Burstedt, and R. S. Johansson, “Control of Fingertip Forces in Multidigit Manipulation,” *J. Neurophysiol*, vol. 81, pp. 1706–1717, 1999.

[11] H. Kinoshita, S. Kawai, and K. Ikuta, “Contributions and co-ordination of individual fingers in multiple finger prehension,” *Ergonomics*, vol. 38, no. 6, pp. 1212–1230, Jun. 1995, doi: 10.1080/00140139508925183.

[12] Sing Bing Kang and K. Ikeuchi, “Toward automatic robot instruction from perception-mapping human grasps to manipulator grasps,” *IEEE Transactions on Robotics and Automation*, vol. 13, no. 1, pp. 81–95, Feb. 1997, doi: 10.1109/70.554349.

[13] J. K. Shim, M. L. Latash, and V. M. Zatsiorsky, “Prehension synergies in three dimensions,” *J. Neurophysiol.*, vol. 93, no. 2, pp. 766–776, Feb. 2005, doi: 10.1152/jn.00764.2004.

[14] V. M. Zatsiorsky, F. Gao, and M. L. Latash, “Prehension Stability: Experiments With Expanding and Contracting Handle,” *J Neurophysiol*, vol. 95, no. 4, pp. 2513–2529, Apr. 2006, doi: 10.1152/jn.00839.2005.

[15] T. Aoki, X. Niu, M. L. Latash, and V. M. Zatsiorsky, “Effects of friction at the digit-object interface on the digit forces in multi-finger prehension,” *Exp Brain Res*, vol. 172, no. 4, pp. 425–438, Jul. 2006, doi: 10.1007/s00221-006-0350-9.

[16] T. Iberall, “Human Prehension and Dexterous Robot Hands,” *The International Journal of Robotics Research*, vol. 16, no. 3, pp. 285–299, Jun. 1997, doi: 10.1177/027836499701600302.

[17] A. A. Amis, “Variation of finger forces in maximal isometric grasp tests on a range of cylinder diameters,” *Journal of Biomedical Engineering*, vol. 9, no. 4, pp. 313–320, Oct. 1987, doi: 10.1016/0141-5425(87)90079-3.

[18] F. T. Hazelton, G. L. Smidt, A. E. Flatt, and R. I. Stephens, “The influence of wrist position on the force produced by the finger flexors,” *Journal of Biomechanics*, vol. 8, no. 5, pp. 301–306, Sep. 1975, doi: 10.1016/0021-9290(75)90082-2.

[19] T. OHTSUKI, “Inhibition of individual fingers during grip strength exertion,” *Ergonomics*, vol. 24, no. 1, pp. 21–36, Jan. 1981, doi: 10.1080/00140138108924827.

[20] S. Radhakrishnan and M. Nagaravindra, “Analysis of hand forces in health and disease during maximum isometric grasping of cylinders,” *Med Biol Eng Comput*, vol. 31, no. 4, pp. 372–376, Jul. 1993, doi: 10.1007/bf02446690.

[21] R. G. Radwin, S. Oh, T. R. Jensen, and J. G. Webster, “External finger forces in submaximal five-finger static pinch prehension,” *Ergonomics*, vol. 35, no. 3, pp. 275–288, Mar. 1992, doi: 10.1080/00140139208967813.

[22] R. Reilmann, A. M. Gordon, and H. Henningsen, “Initiation and development of fingertip forces during whole-hand grasping,” *Exp Brain Res*, vol. 140, no. 4, pp. 443–452, Oct. 2001, doi: 10.1007/s002210100838.

[23] Y.-H. Wu, V. M. Zatsiorsky, and M. L. Latash, “Static Prehension of a Horizontally Oriented Object in Three Dimensions,” *Exp Brain Res*, vol. 216, no. 2, pp. 249–261, Jan. 2012, doi: 10.1007/s00221-011-2923-5.

[24] Z.-M. Li, M. L. Latash, K. M. Newell, and V. M. Zatsiorsky, “Motor redundancy during maximal voluntary contraction in four-finger tasks,” *Experimental Brain Research*, vol. 122, no. 1, pp. 71–78, Sep. 1998, doi: 10.1007/s002210050492.

[25] V. M. Zatsiorsky, R. W. Gregory, and M. L. Latash, “Force and torque production in static multifinger prehension: biomechanics and control. I. Biomechanics,” *Biol Cybern*, vol. 87, no. 1, p. 50, Jul. 2002, doi: 10.1007/s00422-002-0321-6.

[26] J. S. Talsania and S. H. Kozin, “Normal digital contribution to grip strength assessed by a computerized digital dynamometer,” *The Journal of Hand Surgery: British & European Volume*, vol. 23, no. 2, pp. 162–166, Apr. 1998, doi: 10.1016/S0266-7681(98)80165-4.

[27] Z.-M. Li, “Inter-digit co-ordination and object-digit interaction when holding an object with five digits,” *Ergonomics*, vol. 45, no. 6, pp. 425–440, May 2002, doi: 10.1080/00140130210129673.

[28] T. C. Pataky, M. L. Latash, and V. M. Zatsiorsky, “Tangential load sharing among fingers during prehension,” *Ergonomics*, vol. 47, no. 8, pp. 876–889, Jun. 2004, doi: 10.1080/00140130410001670381.

[29] J. K. Shim, M. L. Latash, and V. M. Zatsiorsky, “Finger coordination during moment production on a mechanically fixed object,” *Exp Brain Res*, vol. 157, no. 4, pp. 457–467, Aug. 2004, doi: 10.1007/s00221-004-1859-4.

[30] V. M. Zatsiorsky, F. Gao, and M. L. Latash, “Finger force vectors in multi-finger prehension,” *J Biomech*, vol. 36, no. 11, pp. 1745–1749, Nov. 2003.

[31] T. S. Buchanan, G. P. Rovai, and W. Z. Rymer, “Strategies for muscle activation during isometric torque generation at the human elbow,” *Journal of Neurophysiology*, vol. 62, no. 6, pp. 1201–1212, Dec. 1989, doi: 10.1152/jn.1989.62.6.1201.

[32] F. Gao, M. L. Latash, and V. M. Zatsiorsky, “Maintaining rotational equilibrium during object manipulation: linear behavior of a highly non-linear system,” *Exp Brain Res*, vol. 169, no. 4, pp. 519–531, Mar. 2006, doi: 10.1007/s00221-005-0166-z.

[33] B. I. Prilutsky, “Coordination of two- and one-joint muscles: functional consequences and implications for motor control,” *Motor Control*, vol. 4, no. 1, pp. 1–44, Jan. 2000.

[34] G. P. Slota, M. L. Latash, and V. M. Zatsiorsky, “Tangential Finger Forces Use Mechanical Advantage during Static Grasping,” *Journal of Applied Biomechanics*, vol. 28, no. 1, pp. 78–84, Feb. 2012, doi: 10.1123/jab.28.1.78.

[35] W. Zhang, V. M. Zatsiorsky, and M. L. Latash, "Finger synergies during multi-finger cyclic production of moment of force," *Exp Brain Res*, vol. 177, no. 2, pp. 243–254, Feb. 2007, doi: 10.1007/s00221-006-0663-8.

[36] X. Niu, M. Latash, and V. Zatsiorsky, "Effects of Grasping Force Magnitude on the Coordination of Digit Forces in Multi-finger Prehension," *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, vol. 194, pp. 115–29, Feb. 2009, doi: 10.1007/s00221-008-1675-3.

[37] K.-S. Lee and M.-C. Jung, "Ergonomic evaluation of biomechanical hand function," *Saf Health Work*, vol. 6, no. 1, pp. 9–17, Mar. 2015, doi: 10.1016/j.shaw.2014.09.002.

[38] F. Gao, M. L. Latash, and V. M. Zatsiorsky, "Internal forces during object manipulation," *Exp Brain Res*, vol. 165, no. 1, pp. 69–83, Aug. 2005, doi: 10.1007/s00221-005-2282-1.

[39] R. S. Johansson and G. Westling, "Coordinated isometric muscle commands adequately and erroneously programmed for the weight during lifting task with precision grip," *Exp Brain Res*, vol. 71, no. 1, pp. 59–71, Jun. 1988, doi: 10.1007/BF00247522.

[40] C. J. Winstein, J. H. Abbs, and D. Petashnick, "Influences of object weight and instruction on grip force adjustments," *Exp Brain Res*, vol. 87, no. 2, pp. 465–469, 1991, doi: 10.1007/bf00231864.

[41] B. B. Edin, G. Westling, and R. S. Johansson, "Independent control of human finger-tip forces at individual digits during precision lifting.," *J Physiol*, vol. 450, pp. 547–564, May 1992.

[42] J. R. Flanagan, A. M. Wing, S. Allison, and A. Spenceley, "Effects of surface texture on weight perception when lifting objects with a precision grip," *Perception & Psychophysics*, vol. 57, no. 3, pp. 282–290, Apr. 1995, doi: 10.3758/BF03213054.

[43] R. S. Johansson and G. Westling, "Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects," *Exp Brain Res*, vol. 56, no. 3, pp. 550–564, 1984, doi: 10.1007/bf00237997.

[44] S. Solnik, V. M. Zatsiorsky, and M. L. Latash, "Internal Forces during Static Prehension: Effects of Age and Grasp Configuration," *J Mot Behav*, vol. 46, no. 4, pp. 211–222, 2014, doi: 10.1080/00222895.2014.881315.

[45] V. M. Zatsiorsky, F. Gao, and M. L. Latash, "Prehension synergies: Effects of object geometry and prescribed torques," *Exp Brain Res*, vol. 148, no. 1, pp. 77–87, Jan. 2003, doi: 10.1007/s00221-002-1278-3.

[46] K. J. Cole and J. H. Abbs, “Grip force adjustments evoked by load force perturbations of a grasped object,” *J. Neurophysiol.*, vol. 60, no. 4, pp. 1513–1522, Oct. 1988, doi: 10.1152/jn.1988.60.4.1513.

[47] J. R. Flanagan and J. R. Tresilian, “Grip-load force coupling: A general control strategy for transporting objects,” *Journal of Experimental Psychology: Human Perception and Performance*, vol. 20, no. 5, pp. 944–957, 1994, doi: 10.1037/0096-1523.20.5.944.

[48] R. S. Johansson and G. Westling, “Signals in tactile afferents from the fingers eliciting adaptive motor responses during precision grip,” *Exp Brain Res*, vol. 66, no. 1, pp. 141–154, Mar. 1987, doi: 10.1007/BF00236210.

[49] J. K. Shim, M. L. Latash, and V. M. Zatsiorsky, “Prehension synergies: trial-to-trial variability and hierarchical organization of stable performance,” *Exp Brain Res*, vol. 152, no. 2, p. 173, Sep. 2003, doi: 10.1007/s00221-003-1527-0.

[50] J. C. MacDermid, A. Lee, R. S. Richards, and J. H. Roth, “Individual finger strength:: Are the ulnar digits ‘powerful’?,” *Journal of Hand Therapy*, vol. 17, no. 3, pp. 364–367, Jul. 2004, doi: 10.1197/j.jht.2004.04.006.

[51] V. SKM, W. Zhang, V. M. Zatsiorsky, and M. L. Latash, “AGE EFFECTS ON ROTATIONAL HAND ACTION,” *Hum Mov Sci*, vol. 31, no. 3, pp. 502–518, Jun. 2012, doi: 10.1016/j.humov.2011.07.005.

[52] J. Park, N. Pažin, J. Friedman, V. M. Zatsiorsky, and M. L. Latash, “Mechanical properties of the human hand digits: Age-related differences,” *Clinical Biomechanics*, vol. 29, no. 2, pp. 129–137, Feb. 2014, doi: 10.1016/j.clinbiomech.2013.11.022.

[53] A. V. Savescu, M. Latash, and V. Zatsiorsky, “A technique to determine friction at the fingertips.,” *Journal of applied biomechanics*, 2008, doi: 10.1123/JAB.24.1.43.

[54] M. K. O. Burstedt, B. B. Edin, and R. S. Johansson, “Coordination of fingertip forces during human manipulation can emerge from independent neural networks controlling each engaged digit,” *Experimental Brain Research*, vol. 117, no. 1, pp. 67–79, Oct. 1997, doi: 10.1007/s002210050200.

[55] M. L. Latash, *Synergy*. Oxford University Press, 2008.

[56] Y. Sun, V. M. Zatsiorsky, and M. L. Latash, “Prehension of Half-Full and Half-Empty Glasses: Time and History Effects on Multi-Digit Coordination,” *Exp Brain Res*, vol. 209, no. 4, pp. 571–585, Apr. 2011, doi: 10.1007/s00221-011-2590-6.

[57] W. Zhang, H. B. Olafsdottir, V. M. Zatsiorsky, and M. L. Latash, “Mechanical Analysis and Hierarchies of Multi-digit Synergies during Accurate Object Rotation,” *Motor Control*, vol. 13, no. 3, pp. 251–279, Jul. 2009.

[58] M. Latash, J. Scholz, and G. Schöner, “Motor Control Strategies Revealed in the Structure of Motor Variability,” *Exercise and Sport Sciences Reviews*, vol. 30, no. 1, pp. 26–31, Jan. 2002.

[59] D. Lakens, “Equivalence Tests: A Practical Primer for *t* Tests, Correlations, and Meta-Analyses,” *Social Psychological and Personality Science*, vol. 8, no. 4, pp. 355–362, May 2017, doi: 10.1177/1948550617697177.

[60] T. Aoki, P. R. Francis, and H. Kinoshita, “Differences in the abilities of individual fingers during the performance of fast, repetitive tapping movements,” *Exp Brain Res*, vol. 152, no. 2, pp. 270–280, Sep. 2003, doi: 10.1007/s00221-003-1552-z.

[61] V. M. Zatsiorsky, Z. M. Li, and M. L. Latash, “Coordinated force production in multi-finger tasks: finger interaction and neural network modeling,” *Biol Cybern*, vol. 79, no. 2, pp. 139–150, Aug. 1998, doi: 10.1007/s004220050466.

[62] C. L. Jones and D. G. Kamper, “Involuntary Neuromuscular Coupling between the Thumb and Finger of Stroke Survivors during Dynamic Movement,” *Front Neurol*, vol. 9, Mar. 2018, doi: 10.3389/fneur.2018.00084.

[63] R. Banuvathy and S. K. M. Varadhan, “Distinct behavior of the little finger during the vertical translation of an unsteady thumb platform while grasping,” *Sci Rep*, vol. 11, no. 1, p. 21064, Oct. 2021, doi: 10.1038/s41598-021-00420-5.

[64] M. Barakat, J. Field, and J. Taylor, “The range of movement of the thumb,” *HAND*, vol. 8, Jun. 2013, doi: 10.1007/s11552-013-9492-y.

[65] V. C. Marshall and R. D. Marshall, “Movements of the Thumb in Relation to Peripheral Nerve Injuries,” *Postgrad Med J*, vol. 39, no. 455, pp. 518–525, Sep. 1963.

[66] B. Hirt, H. Seyhan, and M. Wagner, *Hand and Wrist Anatomy and Biomechanics: A Comprehensive Guide*. Thieme, 2016.

[67] P. A. Houglum and D. B. Bertoti, *Brunnstrom’s Clinical Kinesiology*. F.A. Davis, 2012.

[68] X. Niu, M. L. Latash, and V. M. Zatsiorsky, “Prehension Synergies in the Grasps With Complex Friction Patterns: Local Versus Synergic Effects and the Template Control,” *J Neurophysiol*, vol. 98, no. 1, pp. 16–28, Jul. 2007, doi: 10.1152/jn.00058.2007.

[69] A. Riehle and E. Vaadia, *Motor cortex in voluntary movements: A distributed system for distributed functions*. 2004, p. 426.

[70] S. L. Kilbreath and S. C. Gandevia, “Limited independent flexion of the thumb and fingers in human subjects.,” *The Journal of Physiology*, vol. 479, no. 3, pp. 487–497, 1994, doi: 10.1113/jphysiol.1994.sp020312.

[71] S. L. Kilbreath, R. B. Gorman, J. Raymond, and S. C. Gandevia, “Distribution of the forces produced by motor unit activity in the human flexor digitorum profundus,” *The Journal of Physiology*, vol. 543, no. 1, pp. 289–296, 2002, doi: 10.1113/jphysiol.2002.023861.

[72] T. Schneider, G. Buckingham, and J. Hermsdörfer, “Torque planning errors affect the perception of object properties and sensorimotor memories during object manipulation in uncertain grasp situations,” *Journal of Neurophysiology*, vol. 121, Feb. 2019, doi: 10.1152/jn.00710.2018.

[73] M. Santello and J. F. Soechting, “Force synergies for multifingered grasping,” *Exp Brain Res*, vol. 133, no. 4, pp. 457–467, Aug. 2000, doi: 10.1007/s002210000420.

[74] T. Aoki, M. L. Latash, and V. M. Zatsiorsky, “Adjustments to Local Friction in Multifinger Prehension,” *J Mot Behav*, vol. 39, no. 4, pp. 276–290, Jul. 2007, doi: 10.3200/JMBR.39.4.276-290.

[75] G. Cadoret and A. M. Smith, “Friction, not texture, dictates grip forces used during object manipulation,” *J Neurophysiol*, vol. 75, no. 5, pp. 1963–1969, May 1996, doi: 10.1152/jn.1996.75.5.1963.

[76] K. J. Cole and R. S. Johansson, “Friction at the digit-object interface scales the sensorimotor transformation for grip responses to pulling loads,” *Exp Brain Res*, vol. 95, no. 3, pp. 523–532, 1993, doi: 10.1007/BF00227146.

[77] J. Park, B. Baum, Y.-S. Kim, Y. Kim, and J. K. Shim, “Prehension Synergy: Use of Mechanical Advantage During Multifinger Torque Production on Mechanically Fixed and Free Objects,” *Journal of applied biomechanics*, vol. 28, pp. 284–90, Jul. 2012, doi: 10.1007/978-3-642-14998-6_94.

[78] H. Olafsdottir, W. Zhang, V. M. Zatsiorsky, and M. L. Latash, “Age-related changes in multifinger synergies in accurate moment of force production tasks,” *J Appl Physiol*, vol. 102, no. 4, p. 1490, Apr. 2007, doi: 10.1152/japplphysiol.00966.2006.

[79] B. Rajakumar and V. Skm, “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.

[80] C. L. MacKenzie and T. Iberall, *The Grasping Hand*. Elsevier, 1994.

[81] J. Methot, S. J. Chinchalkar, and R. S. Richards, “Contribution of the ulnar digits to grip strength,” *Can J Plast Surg*, vol. 18, no. 1, pp. e10–e14, 2010.

[82] V. M. Zatsiorsky, Z. M. Li, and M. L. Latash, “Enslaving effects in multi-finger force production,” *Exp Brain Res*, vol. 131, no. 2, pp. 187–195, Mar. 2000, doi: 10.1007/s002219900261.

[83] B. Rajakumar, S. Dutta, and V. SKM, “Validity of Mechanical advantage hypothesis of human grasping depends on the nature of task difficulty.” Dec. 29, 2021. doi: 10.21203/rs.3.rs-1058248/v1.

[84] V. M. Zatsiorsky, R. W. Gregory, and M. L. Latash, “Force and torque production in static multifinger prehension: biomechanics and control. I. Biomechanics,” *Biological Cybernetics*, vol. 87, no. 1, pp. 50–57, Jul. 2002, doi: 10.1007/s00422-002-0321-6.

[85] K. Wang, E. P. McGlinn, and K. C. Chung, “A Biomechanical and Evolutionary Perspective on the Function of the Lumbrical Muscle,” *J Hand Surg Am*, vol. 39, no. 1, pp. 149–155, Jan. 2014, doi: 10.1016/j.jhsa.2013.06.029.

[86] J. A. Johnston, S. A. Winges, and M. Santello, “Neural control of hand muscles during prehension,” *Adv Exp Med Biol*, vol. 629, pp. 577–596, 2009, doi: 10.1007/978-0-387-77064-2_31.

[87] B. Poston, A. Danna-Dos Santos, M. Jesunathadas, T. M. Hamm, and M. Santello, “Force-independent distribution of correlated neural inputs to hand muscles during three-digit grasping,” *J Neurophysiol*, vol. 104, no. 2, pp. 1141–1154, Aug. 2010, doi: 10.1152/jn.00185.2010.

[88] S. Kapur, V. M. Zatsiorsky, and M. L. Latash, “Age-related changes in the control of finger force vectors,” *J Appl Physiol (1985)*, vol. 109, no. 6, pp. 1827–1841, Dec. 2010, doi: 10.1152/japplphysiol.00430.2010.

[89] J. R. Flanagan and AlanM. Wing, “Modulation of grip force with load force during point-to-point arm movements,” *Exp Brain Res*, vol. 95, no. 1, Jul. 1993, doi: 10.1007/BF00229662.

[90] D. S. Shah, C. Middleton, S. Gurdezi, M. D. Horwitz, and A. E. Kedgley, “The importance of abductor pollicis longus in wrist motions: A physiological wrist simulator study,” *J Biomech*, vol. 77, pp. 218–222, Aug. 2018, doi: 10.1016/j.jbiomech.2018.07.011.

[91] R. Johansson and G. Westling, “Influences of Cutaneous Sensory Input on the Motor Coordination During Precision Manipulation,” 1984, pp. 249–260. doi: 10.1007/978-1-349-07292-7_17.

[92] A. Kumar and C. Kumar, “THE POLLEX – INDEX COMPLEX AND THE KINETICS OF OPPOSITION,” *Nitte University Journal of Health Science*, vol. 4, pp. 80–87, Dec. 2012, doi: 10.1055/s-0040-1703621.