EFFECT OF GEOMETRIC PROPERTIES AND VARYING TORQUE LEVELS ON MOVEMENT ACCURACY AND GRIP FORCE PATTERN DURING OBJECT MANIPULATION

by

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A Thesis submitted to the Faculty of Graduate Studies of

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Effect of Geometric Properties and Varying Torque Levels on Movement Accuracy and Grip Force Pattern During Object Manipulation

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Of

MASTER OF SCIENCE

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Abstract

Purpose

The purpose of this study was to evaluate movement accuracy and grip force behaviour during object manipulation with finger movements.

Relevance

Many industrial and daily goods handled by hands are spherical or cylindrical (cups, cans, glasses, etc.) and they are often grasped using circular grips. There is a need to analyze object manipulation using two or three fingers as a function of surface curvature under the effect of varying torque levels which more closely simulates everyday tasks. Objects used in daily life are manipulated by holding them either above or below the centre center of mass (CM). These objects can be modelled as a pendulum (P) or an inverted pendulum (IP). In this study, grip type and diameter were systematically varied. Our study looked at movement accuracy during object manipulation at natural speeds.

Participants

Twenty healthy right-handed participants (twelve males; eight females; mean age 27; range 20-35 years) were recruited.

Methods

The experimental task consisted of having the participants perform a visually guided tracking task. The subjects viewed a brightly coloured sinusoidally moving cursor on the monitor and were instructed to move the object in concert with the moving cursor. Finger force data were recorded from the finger force sensors attached to the tips of the

digits. The miniBird motion sensor attached to the object recorded the position in linear and angular planes.

Analysis

The data were processed using Matlab version 7.1. Signal analysis included subsets of whole signal peak to peak and root mean square (RMS). Accuracy analysis was used to analyze time and amplitude error. RMS of the force signals was calculated to analyze changes in grip forces as a function of diameter, grip type and mode of manipulation. Peak Cross Correlation (PCC) was performed between the reference wave and movement trajectory and between movement trajectory and individual finger force signals.

Results

For the scope of tasks performed, neither object curvature nor grip type had any influence on PCC between reference and actual movement trajectory with one exception i.e. effect of grip type, PCC was higher with a three-finger grip than with a two-finger grip in the IP mode. The PCC between movement trajectory and individual finger force profiles was not influenced by object diameter; however PCC between index/middle finger forces and movement trajectory was influenced by grip type. PCC was higher with a two-finger grip than with a three-finger grip. In a three-finger grip, the middle and index fingers produced forces in opposite directions. The individual digit forces were higher with the two-digit than with the three-digit grip in both IP and P modes of manipulation.

Conclusion

A tripod grip offers better movement accuracy and economy of forces when manipulating objects below their CM. Circular objects (8 to 15 cm in diameter), when manipulated with fingers using a tripod grip, do not follow the virtual finger hypothesis.

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Abbreviations

ADL	Activities of Daily Living
ANOVA	Analysis of Variance
AE	Amplitude Error
CM	Centre of Mass
CNS	Central Nervous System
CST	Cortico spinal tract
FA I	Fast Acting type 1 sensory receptors (Meisner Corpuscles)
FSA	Force Sensitive Applications
IP	Inverted Pendulum
M1	Primary Motor Cortex
P	Pendulum
PCC	Peak Cross Correlation Coefficient
PL	Phase Lag
RMS	Root Mean Square
SA II	Slow Acting type I sensory receptors (Merkel's Cells)
SEM	Standard Error Mean
SD	Standard Deviation
Two Finger (i)	Thumb and Index finger grip
Two finger (m)	Thumb and Middle finger grip
TE	Temporal Error

Introduction

Activities of daily living (ADL) require the accurate manipulation of objects of different sizes, shapes and material properties. This necessitates the ability to structure an appropriate grip. Tactile sensation and prehension are very important for optimal hand functioning.

The hand is the end point of the arm and can be moved throughout a large area of space depending on the combined positions of trunk, shoulder girdle, elbow and wrist. Elbow joint movements position the hand close to or away from the body, and combined forearm and wrist movements place the hand in the required position to grasp and manipulate. Grasping, transporting and manipulating objects with our fingers and hand are complicated processes which have attracted considerable scientific attention (Carey et al., 2002; Talati, Valero-Cuevas, & Hirsch, 2005).

Object reaching and manipulation can be partitioned into three distinct components: (1) transport of the arm, (2) orientation of the hand, and (3) grasp (Desmurget et al., 1996). Extensive work has been done to examine neuromuscular control and physical constraints underlying arm function; how wrist, elbow and shoulder movements are formulated and coordinated to transport or position the hand during static grasp (Desmurget et al., 1996; Rand, Shimansky, Stelmach, & Bloedel, 2004). Two schools of thought exist as far as planning of reaching and grasping movements is concerned. The first one proposes the "parallel visuomotor processing" theory. According to this theory one motor task is segmented into functional sub-tasks and all these sub-tasks are implemented and controlled in parallel (Arbib, Iberall, & Lyons, 1985).This theory of "parallel visuomotor processing is supported by various physiological and psychophysical studies. Physiological studies have provided different arguments in support of this break down of movement planning. One such argument is the role of the corticospinal pathways. The pathways responsible for the control of proximal and distal upper extremity musculature are separate (Colebatch & Gandevia, 1989). Another proposed explanation arises from the functional organization of the inferior part of premotor area 6. The premotor cortex contains two types of neurons coding the arm transport and grasp formation respectively. The other one suggests the existence of a functional coupling between the different components of prehension movements. According to these studies any change in size, orientation or location of the object to be grasped influences all the components of movement (Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991).

Vision plays a crucial role in reaching and grasping (Gonzalez-Alvarez, Subramanian, & Pardhan, 2007). Visual information regarding extrinsic properties of the object enables the motor system to transport the hand to the correct distance and in the appropriate direction. Similarly, information regarding intrinsic object properties enables the hand to be in the most efficient position to pick up the object. Several investigators have examined planning and control of finger pre shaping prior to actual object grasp (Ballard, Hayhoe, Li, & Whitehead, 1992; Jeannerod, 1986; Jenmalm & Johansson, 1997; Johansson, Westling, Backstrom, & Flanagan, 2001; Land, Mennie, & Rusted, 1999). They concluded that sensorimotor memories, visual and somatosensory information are important for appropriate grip formation and force output during object manipulation tasks. Somatosensory information is available only upon object contact. On object contact pressure sensors provide critical information regarding control of fingertip forces (Johansson, 2002; Pylatiuk, Kargov, Schulz, & Doderlein, 2006). Touch of the hand is poorer than the eye in resolving fine spatial details; however, it is better than the eye in resolving fine temporal details. Timely feedback controls using tactile or pressure signals are required to accommodate the wide spectrum of geometric and material properties of objects used in daily life, work and recreation/sports.

Geometric properties like size and shape are specific to particular objects. At the micro geometric level; an object is small enough to fall within a single region of skin, such as the fingertip. Each fingertip is equipped with 2000 tactile sensors. The spatial deformation of the skin is coded by slowly and rapidly adapting mechanoreceptors. FA-I (Meisner) and SA-I (Merkel) afferents convey with high acuity both spatial and temporal information about the contact and release of an object. At the macro geometric level, objects do not fall within a single region of the skin, but rather are enveloped with the hands or limbs, bringing in the contribution of kinesthetic receptors and skin sites that are not somatotopically continuous, such as multiple fingers. Integration of these inputs must be performed to determine the geometry of the objects.

Material properties are differentiated into texture, hardness (or compliance), and apparent temperature. Texture comprises many perceptually distinct properties, such as roughness, stickiness, and spatial density. For example, a textured surface has protuberant elements. In a micro texture; the elements are spaced at intervals of the order of microns. In a macro texture, the spacing is one or two orders of magnitude greater (or more). When the elements get too sparse, of the order of 3-4 mm apart or so, it is difficult to characterize the surface as textured. Here movement of the finger across the surface is important.

Compliance perception has both cutaneous and kinesthetic components.

Literature Review

Grasping and manipulating an object is a complex goal-directed behaviour, which requires sensory, motor and executive cognitive processes through feed-forward and feedback mechanism. Object manipulation requires selection of appropriate grip based on an object's intrinsic and extrinsic properties and task demands. Based on this information, a grasp strategy is selected and hand location and orientation is planned (Armbruster & Spijkers, 2006).

Napier (1956) divided grasping patterns into two categories: (1) power grasp and (2) precision grips. Cutkosky (1989) classified power grasp into prehensile and non-prehensile and precision grip into circular (radial symmetry, 3 virtual fingers) and prismatic grip (opposed thumb and two virtual fingers). Prehensile grip was then classified into lateral pinch, circular grip (sphere and disk) and prismatic grip (heavy wrap, adducted thumb, and light tool).

Grip Forces during Object Manipulation

Based on geometric and material properties, appropriate grip forces have to be produced in order to manipulate objects. Grip forces can be divided into two components. The first component is measured along the grip axis and is known as the normal forces which are defined by the line through the centre of the two grasp surfaces. The second component is measured orthogonal to the grip axis and is known as the tangential forces (vertical forces used to lift the object). The normal forces prevent slippage of the grasped object. A major part of the vector sum of the two components (normal and tangential forces) supports the weight of the object (Goodwin, Jenmalm, & Johansson, 1998). In addition, object material and geometric properties create tangential load forces. Sufficient forces which are normal to the grip surfaces and greater than the destabilizing load forces are required to prevent slips (HagerRoss, Cole, & Johansson, 1996). A basic issue in understanding the control of object manipulation is to learn how sensory information is used during feedback processes to adapt fingertip forces quickly to accommodate variations in object shape, slipperiness, weight and torque loads caused by tilting of the object about the grip axis (Jenmalm, Goodwin, & Johansson, 1998).

General Overview of Weight and Friction on Object Manipulation

An approximately linear relationship exists between static grip forces (normal forces) and weight of the object during a slow speed vertical lifting task (Johansson & Westling, 1988). It was shown that during a visually blinded trial where subjects lifted test objects after the weight of the object had been randomly changed, the grip forces were appropriately scaled for trials for constant weight right from the first lift; in case of unexpected changes in object weight, however, the subjects relied on sensory feedback for appropriate scaling of grip forces (Johansson & Westling, 1988). These findings suggest that the grip forces were scaled based on information from previous lift and only after object contact did necessary modifications in grip forces occur.

Friction arises when the fingertips move, or try to move, across the contact area. Friction is a surface or material property. When forces are applied to an object with the fingers, there are forces normal to the surface and there are tangential forces parallel to object surface (also called shear forces). If the surface resistance (friction) is less than the shear force then there will be slip, depending on the magnitude and how much time it takes for the peripheral tactile information to reach the central nervous system (CNS) and to detect the slip and compensate for it.

The ratio between the normal and tangential forces is automatically adjusted to the frictional status at the digit object interface using the well-tuned sensory feedback systems such that adequate safety margin against slip is maintained during different frictional conditions (Jenmalm & Johansson, 1997; Terao, Andersson, Flanagan, & Johansson, 2002). Subjects use greater normal forces when the contact surface has a low co-efficient of friction (e.g. rayon which has a co-efficient of friction of 0.66) than a high co-efficient of friction (e.g. grain sandpaper no. 320 which has a co-efficient of friction of 1.01) (Burstedt, Flanagan, & Johansson, 1999). If the shear force is greater than surface friction force, a slip occurs, and the fingertips start to slide against the object (Fagergren, Ekeberg, & Forssberg, 2003).

When someone is picking up a familiar object between the index finger and the thumb, the motor commands are predetermined to estimate the relevant object properties and thus the grip forces required. Once the object is touched, and if there is a need, adjustment is made as necessary using tactile feedback processes by the CNS to accommodate for the frictional demand at the finger-object contact area (Fagergren et al., 2003). Thus the information about friction is crucial for adjusting the grip forces (normal forces) to avoid slipping and eventually dropping the object. Accidental slips rarely occur because the grip force (normal force) exceeds the minimal force required to prevent slip (the slip force) by a safety margin determined by the skin-object friction (Johansson & Westling, 1984). The CNS is able to estimate the required grip forces. It programs the normal and tangential contact forces as a function of the initial estimated surface friction (grip forces in anticipation of the tangential forces) arising from self-produced movements of objects with predictable physical properties of friction and inertia (Flanagan & Wing, 1993). Different centre's in the cortex utilize tactile information coming from the fingers during object manipulation to update internal (hand system) and external reference frames (object torques, inertia, momentum etc.). Finally, at a more theoretical level, they correct and maintain an internal model of the physical properties of hand-held object.

Other than external object properties force, co-ordination during precision grip is influenced by the intrinsic task variables related to the goal of maintaining a stable grasp (Winstein, Abbs, & Petashnick, 1991). In day-to-day tasks, the loads that potentially destabilize grasp include torques tangential to the grasp surfaces. For example, in a precision grip task, tangential torques occur when an object is titled around the grip axis (line joining the fingertips) that does not pass through the center of gravity of the object. Tangential torques can also arise because the normal force is distributed across the skin–object contact area rather than being focused at one point (Howe & Cutkosky, 1996).

Processes Involved in Object Manipulation and their Higher Centre Control

In case of linear one-axis movement, the initial contact with the object marks the beginning of the preload phase, once the grip force (normal and tangential force) has overcome the weight of the object then the transitional phase begins, ultimately followed by the parallel decrease in grip force to load force in order to replace object (unload phase).

Predictive control is mainly employed for learned manipulation of objects and where no significant stability challenges are expected. The brain relies on feedforward control for objects with stable and predictable properties. Studies have shown that the forces initially developed during lift off are predicted based on the force requirements during the previous lift (Johansson & Westling, 1988). Initial forces used are based on the experience and memory information of the object previously manipulated. There exist sensorimotor memories that represent both important physical properties of the objects to be manipulated and the appropriate magnitude parameters of the motor commands. The use of vision to estimate object weight, centre of mass (CM), and surface friction properties also plays an important role in anticipatory parameter control prior to lift off phase as it helps to retrieve information about an object's properties and helps to develop appropriate grip forces in advance of the actual grasping and lifting. The CNS is able to adapt motor commands according to task demands in a feedforward manner (Ghez, Hening, & Gordon, 1991; Johansson & Cole, 1992; Lacquaniti, Borghese, & Carrozzo, 1992; Wolpert & Miall, 1996; Flanagan & Wing, 1997). This indicates that physical properties of common objects are indeed represented in memories that are used for anticipatory parameter control of the force output.

The ability of humans to learn to identify unfamiliar objects for anticipatory parameter control of the force output for object weight has also been investigated. With unfamiliar objects, it appears that subjects initially obtain weight estimates by size-weight associations using a default density estimate that is in the range of common densities. These size-weight associations are efficiently used for classes of related objects (Gordon, Forssberg, Johansson, & Westling, 1991a; Gordon, Forssberg, Johansson, & Westling, 1991b; Gordon, Forssberg, Johansson, & Westling, 1991c).

However, in many other cases of irregular shaped objects, fluid filled objects or multi axis movements, inertial effects, torque/momentum effects and accuracy issues will cause load force to change in unpredictable ways as the object moves or the limb changes angles. Manipulation of objects with curved surfaces under torque loads requires sensory information over and above the visual cues. Sensory feedback provides information about the change in load force occurring as a result of an object's acceleration or deceleration. This information is integrated with the information from proprioceptors and necessary corrections or adjustments are made in the ongoing movement plan in order to prevent object slip and to achieve the goal.

Sufficient normal forces are required to overcome the load forces to accelerate the object and simultaneously to produce minimum tangential force in accordance with the object surface friction conditions. The load forces depend on many factors like the location of the contact surfaces relative to the grasped object's center of mass, on the object's weight, precise location of the centers of pressure of each of the digits, the amplitude of the tangential torques exerted by the subject and the amplitude of the horizontal (grip) forces (Baud-Bovy & Soechting, 2002). During day-to-day manipulations, object torque is encountered and this will require the tangential forces to control for it, if the tangential forces become greater than the friction forces a slip will occur, in that case moment to moment feedback information is essential in order to prevent the object from slipping. In addition, the actual point of contact of the fingers with the object is only known at the beginning of the movement. Each contact point can create a different axis of rotation. Tactile sensors along with proprioceptors detect this, provide this information to the CNS, and hence necessary adjustments can be made. The time delays associated with feedback processing arise from electro-mechanical muscle contractile time. The minimal time delay for these feedback loops is approximately 70-100 ms (Kawato et al., 2003).

The primary motor cortex (M1) and its descending projection to the spinal cord in the corticospinal tract (CST) are crucial for the normal control of hand and finger movements. Various studies that have used neuro-imaging techniques have shown that M1 is active during many types of voluntary hand movements (Ehrsson et al., 2000; Milner, Franklin, Imamizu, & Kawato, 2007; Roland & Zilles, 1996). M1 neurons can exert a facilitatory or inhibitory influence on the motorneuron pools of different muscles; since all M1 output neurons are excitatory. Thus, the output of M1 facilitates contraction of those muscles, actively generating the intended movement and to suppress unintended motion of other body parts via CST.

The somatosensory cortex and the parietal association areas are important for the recognition of tactile objects. The somatosensory cortex receives both cutaneous and proprioceptive information, integrates it, and sends it to M1. M1 plays a significant role not only in motor execution but also in spatial and temporal processing of events. It contributes to the cognitive events that form motor learning (Carey et al., 2006). The role of cerebellum is more significant than M1 in task dynamics (Milner et al., 2007). The cerebellum is involved in the feedback processes that are used to stabilize the arm and control the fingers. It acts as a feedback controller (i.e. based on information obtained from the tactile sensors and proprioceptors, the cerebellum aids in making timely corrections to prevent slip and hence restore stability). There is a consistent interaction between the cerebellum and the primary motor cortex and this interaction is crucial for early learning of motor sequence tasks (Penhune & Doyon, 2005). Activity in the cerebellar cortex decreases with learning and this is related to the reduction in climbing fibre input resulting from decreasing error signals as learning proceeds (Doyon et al., 2002).

Increased activity in M1 with learning has been hypothesized to be related to changes in connectivity and synaptic strength related to practice and later storage of motor patterns (Kleim et al., 2004; Nudo, Wise, SiFuentes, & Milliken, 1996). The optimized movement parameters for the learnt movement are encoded in M1 and other motor related structures. Greater brain activation is shown during performance of tracking tasks rather than simple movements. Visuomotor tracking tasks involve use of larger sensorimotor networks including premotor cortex, posterior parietal cortex, motor cortex, insula, cerebellum as well as basal ganglia and thalamus (Oreja-Guevara et al., 2004).

Effect of Object Curvature and Grip Type on Object Manipulation

Several studies have examined the effect of object curvature on the performance of static hold tasks and simple lifting tasks using a precision grip. These studies have looked at the grip force profiles and the tangential/vertical forces, and how they change as a result of change in object curvature. Jenmalm and Johansson (1997) studied the effect of object curvature on grip force and vertical force. The objective of the study was to investigate the importance of visual and somatosensory information for adaptation of fingertip forces to object shape in a lift and hold task using precision grip and to study the effect of object curvature on finger forces. The task was a simple lift and hence no significant torque challenges were encountered. The authors used grain sandpaper over all objects to control for friction. The objects used were tapered at -30, 30 and 0 degrees. The authors found that the horizontal forces were influenced by the shape of the object with the forces increasing with an increase in surface angle. This effect was noted from the beginning of the lift. However there was no significant effect of the object shape on the vertical forces. The authors also found that vision had a significant role in force regulation and stated that conditions in which vision and tactile sensation were intact the forces were appropriately scaled right from the time of object lift and were not influenced by the previous lift. However in trials where only visual feedback was available, the horizontal forces were considerably stronger throughout the trial; this indicates the role of sensory feedback in appropriate force scaling.

Jenmalm et al. (1998) studied the effect of surface curvature on fingertip forces in a simple lifting task. The authors looked at the influence of surface curvature on critical grip to load force ratio (slip ratio) at which frictional slip occurred. The object was changed through a range of curvatures from concave to flat to convex. Friction was controlled for by covering the surface of the object with silicon carbide grains. The task was a vertical lift (using a thumb and index finger grip) and hold using elbow flexion followed by a controlled release of the object. The critical grip to load force ratio was measured at the time of release. This ratio was maximum for the flat surface and decreased for the concave and convex surfaces depending upon the weight of the object. Since two variables were changed and with increasing weight, torque increased, it is difficult to judge that which factor contributed to increase in slip ratio. The surface curvature showed no significant influence on grip forces during the static hold phase irrespective of object weight. Surface curvature did not influence the duration of the load phase or the peak rate of grip force increase.

Lastly, the authors concluded that for the type of experimental task performed, grip force at 10, 50 and 90% of static load was not influenced by surface curvature. Thus in a controlled slow, vertical lift task the above findings state that the grip force is not influenced by surface curvature. In everyday life, however, the tasks are dynamic in nature (i.e. significant torsional loads are expected) and hence these results cannot be generalized to object manipulation during ADLs.

Goodwin et al. (1998) analyzed the control of grip forces to match changes in tangential torque in a lift and tilt task using elbow flexion and wrist radial flexion. The test object had two symmetrical grasp surfaces and a 31 cm long aluminum rod that protruded orthogonally to the axis between the centers of the grasp surfaces. Pairs of exchangeable matching spherically curved grasp surfaces were attached to the object. The object curvature ranged from 20mm concave grasp surface to 5 mm convex grasp surface. The task involved lifting the object with a precision grip (using thumb and index finger), then tilting it 65 degrees, and having a controlled release of the object. Digit-object friction was controlled by covering the grasp surfaces with silicon carbide grains. The grip forces were measured along the grip axis defined by the line through the centers of the two grasp surfaces and the tangential torque was the torque about the grip axis. The grip force measurements were taken at 10, 50 and 90% of tangential torques from before tilt to the period where the object was maintained in a tilted position. The author concluded that the balance between the grip forces and the tangential torque was influenced by surface curvature and that the grip forces at any given torque increased parametrically with increasing curvature. The author also concluded that the modification of grip force to surface curvature was present right from the start of the trial; however the grip forces as per the method section were measured at predetermined target torques (i.e. 10, 50 and 90%). In addition, since data about grip force at time of object contact and until 10% of tangential torques is not available, it is difficult to contend that visual geometric cues alone were responsible for grip force modulation (feed forward control) to object shape. The task in the experiment was performed at a very slow speed (approximately 20sec) and hence is comparable to a static task and the findings cannot be generalized to dynamic tasks requiring accuracy.

Flanagan, Burstedt and Johansson (1999) examined the control of fingertip forces in a multi digit task. The task involved a simple lift of a cube (covered with grain sand paper) weighing 0.2kg, first using thumb, index and middle finger and then using thumb, index and ring finger. The object was to be lifted 5cm in four seconds. The subjects did not receive any instructions about the orientation of the object during the lift. There was no significant tilt of the object noted (i.e. both elevation and roll angles were within plus or minus one degree). It is essential to note that under the experimental conditions, no significant torque was created as the chances of object tilt were minimal. Manipulation in daily life requires far more precision and involves moment-to-moment torque challenges and thus this finding cannot be generalized. The normal forces increased in phase with tangential load at each digit. The authors defined tangential load as a sum of tangential force (load) and tangential torque but if tangential torque was minimal then the experiment is only testing the relationship between normal force and load force which has already been proven in the past. Thus the study throws no light on the fingertip forces in a tripod grasp where significant torque challenges are imposed. The authors found that the forces exerted by the three digits were all in different directions and did not oppose one another (therefore they did not follow the virtual finger hypothesis). These findings contradict the virtual finger hypothesis (Baud-Bovy & Soechting, 2001).

Jenmalm, Dahlstedt and Johansson (2000) investigated the role of visual and tactile sensory information in adaptation of the grip forces to surface curvature, under significant torque loads. The author also tested the influence of surface curvature on rotational yield of grasp during torque loading. The test protocol involved lifting an elongated object, of 50 gms weight coated with silicon carbide grains, using a thumb and index finger precision grip under various sensory conditions. Rotational yield of the grasp was computed as the time varying difference between the fingertip placement and the object elevation angle that occurred after the start of the torque loading phase (i.e. from the time of torque load increase until object lift off). The study showed that the grip forces were strongly influenced by surface curvature (i.e. the grip forces were higher for more curved surfaces right from the start of the trial). The study also showed that the object elevation was maximal towards lift off and then it declined after lift off. The author has explained that the subject altered the positioning of the fingertips to prevent object rotation.

Another possible explanation for this could be that in the initial phase of the trial the forces were being scaled according to object properties, but once enough sensory information was available, appropriate grip forces could be generated to prevent the object from rotating. From the graphs it is obvious that no significant differences in torque loads were observed over the range of surface curvatures and this could be explained by the physical properties of the object used (i.e. weight 50 gms and covered with silicon carbide grains). Hence in this study no significant torques were created that would allow us to look at the influence of surface curvature on grip forces during torque loading.

Few studies have examined the effect of orientation and location of the fingers on the grip forces in a multi-fingered static hold task. Baud-Bovy and Soechting (2001) studied the control of direction of grip forces in a multi-fingered grasp. The authors varied the orientation and location of the thumb, index and middle finger during a simple slow vertical lifting task. Rough sandpaper was rubbed over the objects to control for friction as a variable. The authors showed that there was no significant influence of orientation of contact surfaces on the magnitude of the horizontal grip forces (normal forces) during the static hold phase of the experiment. The study also showed that for all combination of finger orientations the thumb forces were greater than the index and middle finger forces. However, the orientation of the contact surfaces seemed to have a significant effect on the direction of the force. The direction of the thumb force was influenced only by the thumb contact surface whereas the direction of the index and middle finger forces were dependent on orientation of both these contact surfaces. The direction of the thumb force was directed midway between the two fingers. The author suggested that the control of a tripod grasp can be explained using the virtual finger hypothesis (i.e. the thumb opposing a single virtual finger which lies midway between the two actual fingers).

In another study by Flanagan et al. (1999), a similar static hold task was used and different finger orientations were used; the author concluded that stable grasp was obtained with different combinations of forces in horizontal plane of the object. The force vectors generated by any three digits always intersected at a single point in the horizontal plane because the total force and torque acting on the object were always zero.

Kinoshita, Kawai, and Ikuta (1995) studied the effect of object weight, surface friction and grip type on grip forces. The author showed that the object weight and surface friction affected the total force magnitudes. The pattern of force distribution amongst digits was not affected by change in any of the two variables. For the three-finger precision grip task, the author showed larger static grip forces for the middle finger than for the index finger. Kinoshita, Murase, and Bandou (1996) investigated the position and grip forces of individual fingers when holding cylindrical objects with varied weights and sizes using a cylindrical grip. The experimental task is not well defined; the author has only identified that the object was vertically lifted from the upper direction using 5, 4, 3 and 2 finger circular grasps with no specific instruction regarding placement of the fingers. The objects were 5, 7.5 and 10 cm in diameter and were covered with polished Perspex plastic (a relatively non slippery surface). A protractor was attached at the bottom surface of the object for measuring finger position. Static grip forces were measured at 7-8 sec of the 10 sec hold period using a force transducer attached to the cylindrical object. The author concluded from the study that under the given experimental conditions the finger positions were not affected by weight, gender, hand strength and hand size; however the grip mode did affect finger positions. The total grip forces changed with weight, diameter and grip mode. The grip forces were larger for the 5 and 10cm object than for the 7.5cm for a 5 digit grip. The grip forces increased as the number of fingers used decreased. Amongst the fingers used, the thumb contribution was maximum, followed by either the ring or little finger. The index finger contribution was always the smallest. No significant gender differences were noted in grip forces. The effects of hand size and strength on total and individual finger forces were small.

A recent study by Pylatiuk et al. (2006) looked at the finger grip forces during manipulation of household objects (i.e. glass bottles of different sizes, coffee tin lid and zipper). The authors used conductive polymer pressure sensors for recording grip forces. The study looked at the relationships between age and force, hand size and force and between force distributions at different periods of manipulation. The tasks included lifting two glass bottles of varying sizes and weights, simulating a pouring task, closing the lid of a coffee tin, and zipping and unzipping a zipper. For the first task a five finger grasp was used for both bottles and the author found that on an average the force distribution was in the order of thumb > middle finger > index finger > ring finger > little finger. The total forces used for the manipulation of large bottle were more than those used for the manipulation of small bottle; however the effect of weight and surface diameter on this factor cannot be segregated. For the second task the forces were in the order of thumb >ring>little>middle $\geq$ index finger. For the third task the forces were more at the index finger compared to the thumb.

The author concluded that the force distribution amongst fingers was independent of age and hand size. This study does throw some light on the way forces are distributed amongst fingers; however, there are too many variables in the performance of the tasks (weight, size and task protocol) and the effect of no single variable can be computed.

Summary

Finger forces have been studied during either the hold phase of a lifting task or during a slow movement of the object using elbow or wrist joint, in which case external destabilizing forces are minimal. There is a need to extend this information to understand grip force regulation during dynamic object manipulation tasks using 2 and 3 finger precision grips under varying levels of torque. Most of the studies that have addressed force control during simple transport tasks have not looked at movement accuracy during task performance. Moreover, the instruments used for force measurement tended to be strain gauge devices or sensor equipped gloves (Pylatiuk et al., 2006). The strain gauge needs to be instrumented on the object. Hence, if the fingers move relative to the object surface or vice versa then the forces will not be recorded besides they are typically large sensors and cannot be used to instrument small objects. The sensor equipped gloves compromise the tactile abilities of the hand. Few studies have used small versatile sensors that are taped directly to the hand for studying grip forces at different contact points in the performance of functional tasks (Pylatiuk et al., 2006). Many industrial and household items are spherical or cylindrical (cups, cans, glasses, bottles) and they are often grasped using circular grips (Kinoshita et al., 1996). There is a need to analyze object manipulation using 2 and 3 fingers as a function of surface curvature under the effect of varying torque levels which more closely simulate everyday tasks and thus include the effects of many physical properties of common and complex objects in normal use.

Objects used in daily life are manipulated holding them either above the CM (such as drinking from a bottle) or holding them below the CM (such as drinking from a wine glass). These can be modeled as a pendulum (holding the object above the axis of movement) or as an inverted pendulum (holding the object below the axis of movement).The grip posture used changes with diameter. In this study, grip type and diameter were systematically changed. Our study looks at object motion at natural speeds where movement accuracy is addressed.

Purpose

The purpose of this study was to look at movement accuracy and grip force behaviour during object manipulation with finger movements and not simply object transport in space with static finger grip.

For this purpose, diameter of the object, grip type and torque modes were systematically varied. Cylinders of 8, 10.5 and 15 cm diameter were manipulated using finger movements (two and three fingers) in two modes of torque: pendulum (P) and inverted pendulum (IP). The movement and force signals recorded during the task were used to quantify amplitude and temporal errors and peak cross correlation (PCC) was used to study the similarity between the forces and object motion signals.

Objectives

1. To quantify the differences in movement accuracy based on object curvature and type of grip in two modes of movements i.e. pendulum and inverted pendulum. The miniBird data was used to compute absolute and relative amplitude and temporal errors in motion signals. The miniBird records movement trajectories in three linear and three angular axes. These movement trajectories were recorded for all tasks. PCC of the reference frame with the actual movement signal was used to understand the similarity between the two signals.
2. To analyze the relationship between individual finger force signals and movement trajectory under influence of diameter, varying torque and 2/3 finger usage.

3. To study the magnitude of forces required when using two fingers (thumb to index and thumb to middle finger) v/s three fingers (thumb index and middle finger) for different diameters and modes of manipulation.

The amounts of grip forces exerted by each finger during different phases of movement reflect the contribution of different fingers during task performance.

Methods

Subjects

Twenty right-handed participants (twelve males; eight females; mean age 27; range 20-35 years) were recruited from students and staff at the University of Manitoba and Health Sciences Centre via advertisement. Subjects were excluded if there was a past history of upper limb pathology with residual deficits, recent injury to the right arm, inability to follow instructions for the experimental task and if there was a history of neurological impairment affecting balance, vision or coordination. Subjects were fully informed about the procedure and an informed consent was obtained once the participants had read the Participation Information and Consent Form and all questions had been answered.

Power calculation for this study was not performed. Based on similar studies done in the past on a sample size of 10 or less it was estimated that 20 subjects would provide reliable results that allowed credible conclusions to be drawn. Ethical approval was obtained from the Health Research Ethics Board (HREB) Bannatyne Campus, University of Manitoba (H2007:158).

Instruments and Data Recording

1. MiniBird motion tracker: The miniBird pulsed DC magnetic tracking system (Model 800) with miniature motion sensor (Ascension Technologies, Burlington, VT, USA) was used to instrument objects. It is reliable and allows precise measurement of 3D spatial position and orientation of any object sampled at 35 Hz. The sensor is capable of recording linear and angular positions along the X,

Y, and Z axes. The reference frame was aligned with the orientation dimple (black dot on the sensor head) facing up with the cord towards the magnet. In this position linear x, y and z follow the right hand rule. Orientation angles were defined as rotations about the x (roll), y (elevation) and z (azimuth) axes of the sensor. This study used a sensor head of the size of 8 mmx8mmx18mm and 0.8 g in weight.

Each object was instrumented with the miniBird at a marked location to ensure correct placement with each participant and over time. The position of the object relative to the magnet was kept fixed.

2. Finger Force sensors: Individual miniature force sensors (Force Sensitive Applications (FSA), Verg Inc. Winnipeg, Canada) were used to measure the contact forces between the finger digital pads and the object. These were taped to the antero-lateral aspect of the digital pads of thumb, index and middle finger using two-sided tape. These pressure sensors were configured to record up to 10 Psi force at a sampling frequency of 125 Hz. The flexible peizo resistive sensors (1 cm square) were ultra thin and did not interfere with object manipulation once the surface texture (co efficient of friction) was modestly adjusted. Seren wrap was used to adjust the coefficient of friction. Placing the sensors on the fingers instead of on the object being manipulated allowed greater versatility and spatial resolution. These force sensors record contact forces (normal forces) during task performance. An electronic synchronization system was used so that the FSA triggered the miniBird. Movement signals from the miniBird and force signals from the FSA were thus synchronized.

Experimental Set-up and Task Protocol

The objects used for the experiment consisted of three sizes of cardboard cylinders measuring 8, 10.5 and 15 cm in diameter. A cloth tape was pasted to the outer side of the objects to equalize the weight. All objects weighed 50gms.

The objects were manipulated using a prismatic grip (a grip by the tips of the digits in which the thumb and the fingers oppose each other) (Zatsiorsky & Latash, 2004). The three grips that were used for object manipulation were

1. three-finger precision grip using thumb, index and middle finger
2. two-finger precision grip using thumb and index finger
3. two-finger precision grip using thumb and middle finger

The experimental task consisted of performing a visually guided open loop tracking task. The subjects viewed a brightly colored sinusoidally moving cursor on the monitor and were instructed to move the object in concert with the cursor. The amplitude and speed of the cursor were predetermined and based on natural movement. Sinusoid motion of 8 (repeated) cycles at a frequency of 0.4 Hz was performed. Preliminary testing showed that 10% of the height of the computer screen at a frequency of 0.4 Hz was the most comfortable for participants. A visually guided tracking task was selected, as past literature has shown that tracking tasks are valuable assessment tools and they produce consistent and reproducible waveforms (Carey et al., 2002; Kriz, Hermsdorfer, Marquardt, & Mai, 1995; Yamanaka et al., 2005). A sinusoidal wave form was used to control spatio-temporal parameters in the same way as a metronome. Tracking tasks are sensitive to detect small changes in force control and joint movement control and are reliable and repeatable (Carey, Patterson, & Hollenstein, 1988). A custom software program written for Linux OS was created to control motion of the moving cursor. The custom software also synchronously logged and saved (100Hz) the position coordinates of the on-screen moving target cursor and the position and orientation coordinates of the measured motion signals of the miniBird.

The participants washed their hands five minutes before the trial. The participants were seated in a regular height office chair with the shoulder in 15 degrees of forward flexion and neutral rotation, elbow flexed to 90 degrees and the forearm in mid prone position supported over a table in a trough to minimize forearm pronation and supination and shoulder external and internal rotation. The finger sensors were taped to each subject's right hand and wrist. Using each of the above grips, the subject performed 1 trial of 8 cycles of movement, manipulating the object as a pendulum and inverted pendulum. The order of presentation of each of the independent variable was randomized to minimize the potential learning effect or order effect. Each object was instrumented with the miniBird at a marked location. The subjects were handed the object and asked to begin object manipulation on a count of three. It was emphasized that the wrist was not to be used to complete the task; all object manipulations were to be performed using index and/or middle finger flexion-extension and thumb rotation.

Dependent and Independent Variables

Independent Variables

1. Diameter of the object
2. Type of grip i.e. two finger precision grip (thumb to index or thumb to middle finger) and three finger precision grip
3. Type of movement (i.e. pendulum, inverted pendulum)

Dependent Variables

1. Temporal error
2. Amplitude error
3. RMS of force signals collected from each digit
4. r value

The temporal and amplitude error calculated using miniBird data provided information about movement accuracy over a range of independent variables. RMS values calculated from the force signals provided information about total grip forces (normal and tangential) over a range of independent variables. A cross-correlation was conducted between movement trajectories and force signals during each object manipulation and under each torque condition in order to study the effect of each independent variable on the grip forces used. A cross-correlation is a measure of similarity of two signals, commonly used to find features in unknown signals by comparing them to a known one.

Data Analysis

The data were processed using Matlab version 7.1(The Math Works, Natick, MA) and then exported for offline analysis. This software program can perform signal and accuracy analysis. Signal analysis included subsets of whole signal peak to peak and RMS. Accuracy analysis was used to compare the reference waveform to the performance waveform and was to analyze time and amplitude error. The on axis movement (i.e. the primary axis of movement) was analyzed for amplitude and temporal errors. RMS of the force signals was calculated for different diameters of objects to analyze changes in grip forces as a function of diameter.

RMS of the force signals was done for different types of manipulation (i.e. as an upright and an inverted pendulum). This data were further analyzed to study the behaviour of the grip forces at individual digits in concert with the movement trajectories. A cross-correlation function was performed between performance movement waveform and the force signals for each individual digit to understand the role of each digit in producing/controlling movement. Another cross-correlation was performed between the reference wave and movement trajectory to see if movement accuracy was better using a particular grip type.

Statistical Analysis

A repeated Analysis of Variance (ANOVA) was used to evaluate the influence of object diameter (8, 10.5 and 15cm), torque levels (pendulum and inverted pendulum) and type of precision grip (two- versus three-finger) on the amplitude accuracy, temporal accuracy and grip forces (normal and tangential forces). A p value of 0.05 was considered statistically significant. Type I error was controlled by first performing a multivariate analysis of variance and univariate tests were considered only if the multivariate test was significant ($p < .05$), this kept the type I error rate at 5% (Hummel & Sligo 1971). Peak cross correlation coefficient (PCC) was used to identify the possible relation between force and object movement trajectory and between movement and target trajectory.

Result

Typical plots of movement trajectory and force profiles of a single subject during different task performance are shown in figures 1, 2 and 3. For all grip and diameter conditions in the P and IP mode the forward rotation of the object coincided with the forward maximum position of the actual movement trajectory and the backward rotation of the object coincided with the backward maximum position of the actual movement trajectory. A few consistent findings were evident in all plots, for all object diameters, grips and modes of manipulation. The actual movement waveform showed a rhythmical cyclic pattern while tracking the sinusoidal target trajectory. In many cases, plateau periods were evident at the maximum backward rotation of the object in the pendulum mode.

For the three-finger grip, (figure 1(a), (b) and 1 (c)) movement cycles were evident in all finger force profiles. In both modes of manipulation all finger force profiles exhibited a regular cyclic pattern with a plateau at their off period with one exception i.e. thumb force profiles in the pendulum mode exhibited irregular cyclic pattern. In the inverted pendulum mode, during the forward rotation of the object the thumb and middle finger force profiles increased indicating that the load is transferred to the thumb and middle finger. Conversely, during the backward rotation of the object the index finger force profiles increased indicating that the load was transferred to the index finger. This was opposite in the pendulum mode. Concentric contraction of thumb flexors and adductors and index finger internal rotators is required produce the forward rotation of the object in the P mode whereas concentric contraction of the thumb extensors and adductors and eccentric contraction of the middle finger internal rotators is required to produce the forward rotation of the object in the IP mode. Concentric contraction of the thumb extensors and abductors and concentric contraction of middle finger internal rotators is required to produce the backward rotation of the object in the P mode. Concentric contraction of thumb flexors and adductors and eccentric contraction of finger external rotators is required to produce the backward rotation of the object in the IP mode. Thus to produce the same type of rotation of object in two different modes of manipulation forces at different digits had to increase/decrease based on the external destabilizing forces (gravity and torque) acting on the object.

For the two-finger grip (i), (figure 2) movement cycles were evident in both thumb and index finger force profiles with one exception. The index finger forces profiles exhibited irregular cyclic pattern in pendulum mode. In both modes of manipulation thumb force profiles showed a regular cyclic pattern with a plateau at their maximum and at their off period. The index finger force profiles showed an irregular pattern with cycles seen only in the inverted pendulum mode. In the inverted pendulum mode during forward rotation of the object, the index finger force profiles increased indicating that the load is transferred to the index finger. In both IP and P thumb force profiles increased during the backward rotation of the object. Concentric contraction of thumb flexors and adductors and finger external rotators is required to produce the forward rotation of the object in the P mode. Concentric contraction of the thumb extensors and abductors and eccentric contraction of the finger internal rotators is required to produce the forward rotation of the object in the IP mode. Concentric contraction of the thumb extensors and abductors and concentric contraction of finger internal rotators is required to produce the backward rotation of the object in the P mode. Concentric contraction of thumb flexors and adductors and eccentric contraction of finger external rotators is required to produce the backward rotation of the object in the IP mode. For both modes of manipulation amplitude of index finger force profiles were larger than thumb.

For the two finger grip (m), (figure 3) movement cycles were evident in both thumb and middle finger force profiles with one exception. The middle finger in pendulum mode exhibited irregular cyclic pattern. In both modes of manipulation thumb force profiles showed a regular cyclic pattern with a plateau at their maximum. The middle finger force profiles showed an irregular pattern with cycles seen only in the inverted pendulum mode. In the inverted pendulum mode during the forward rotation of the object the middle finger force profiles increased indicating that the load is transferred to the middle finger. The thumb force profiles increased during the forward rotation of the object in IP mode and during the backward rotation of the object in P mode. Thus in the inverted pendulum mode the load was transferred to the thumb at forward object rotation and this was opposite for the pendulum mode. Similar type of muscle contractions as seen for two finger grip (t-i) would be required to produce movements using thumb and middle finger grip. For both modes of manipulation amplitude of middle finger force profiles were larger than thumb.

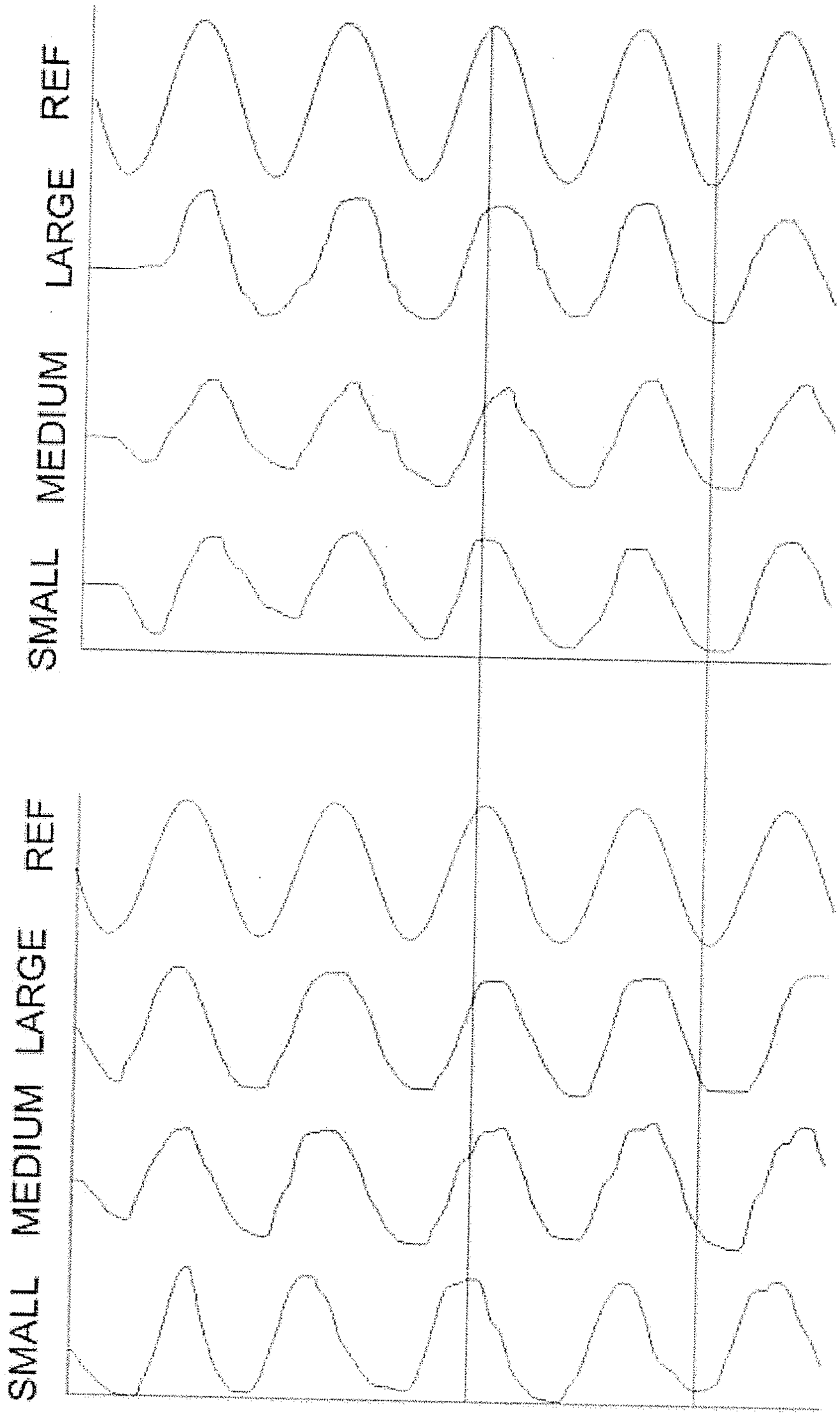


Fig 1a. Shows raw data of a single subject when manipulating the 3 cylinders using three finger grip. Top panel is IP and bottom panel is P.

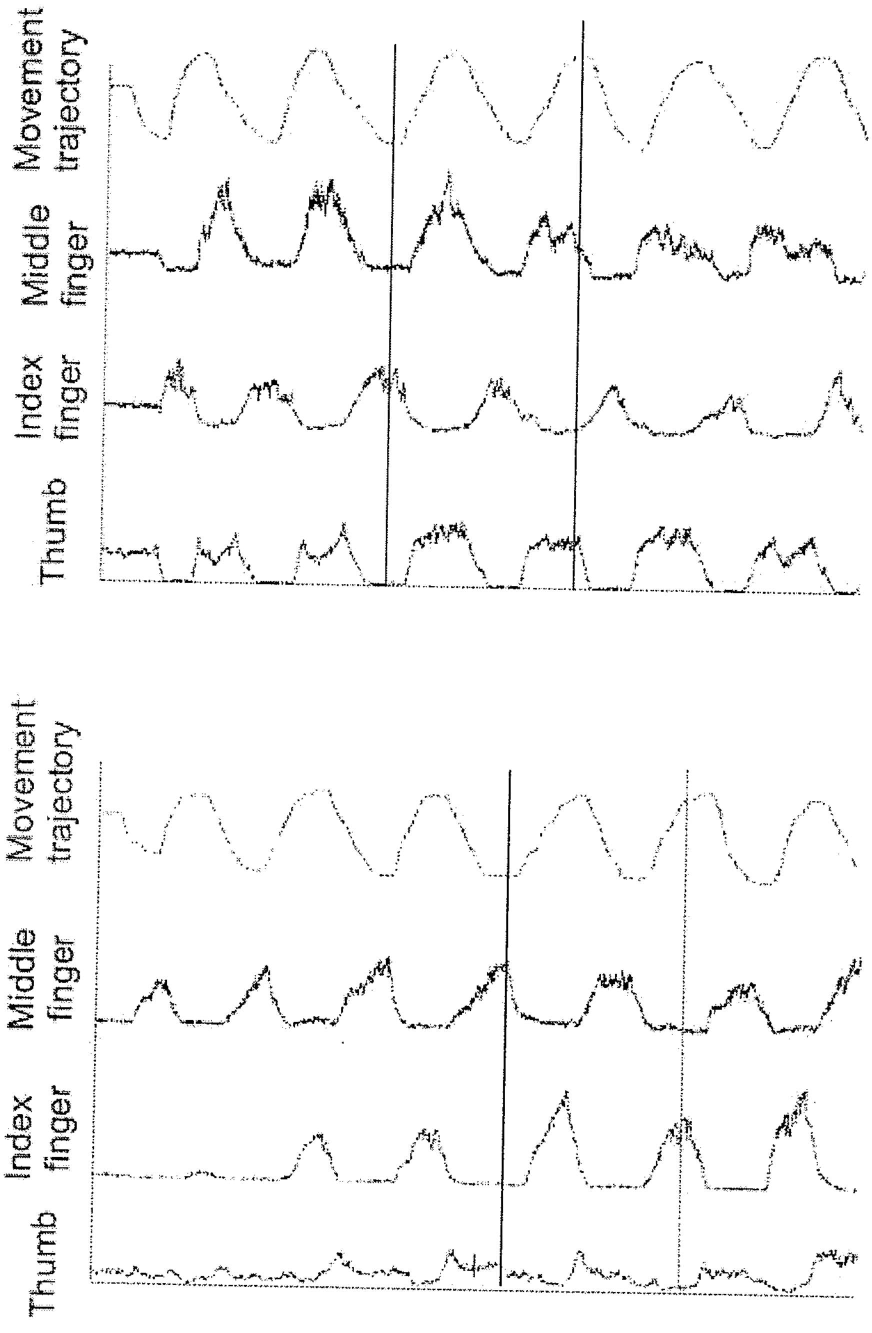
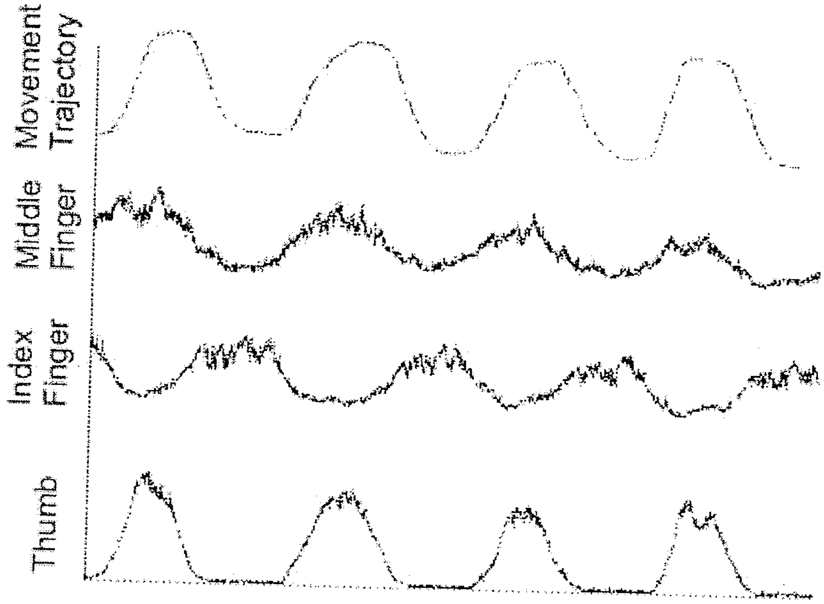


Fig 1b. represents raw data of a single subject when manipulating a medium size cylinder using three finger grip. Top graph is for inverted pendulum and bottom graph is for pendulum .



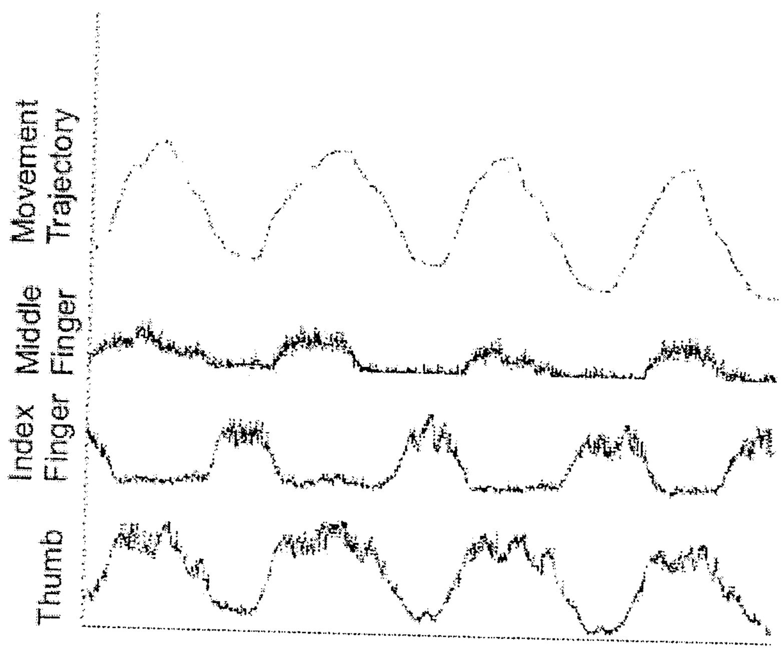


Fig 1c. represents raw data of 2 subjects when manipulating a medium size cylinder using three finger grip in the inverted pendulum mode.

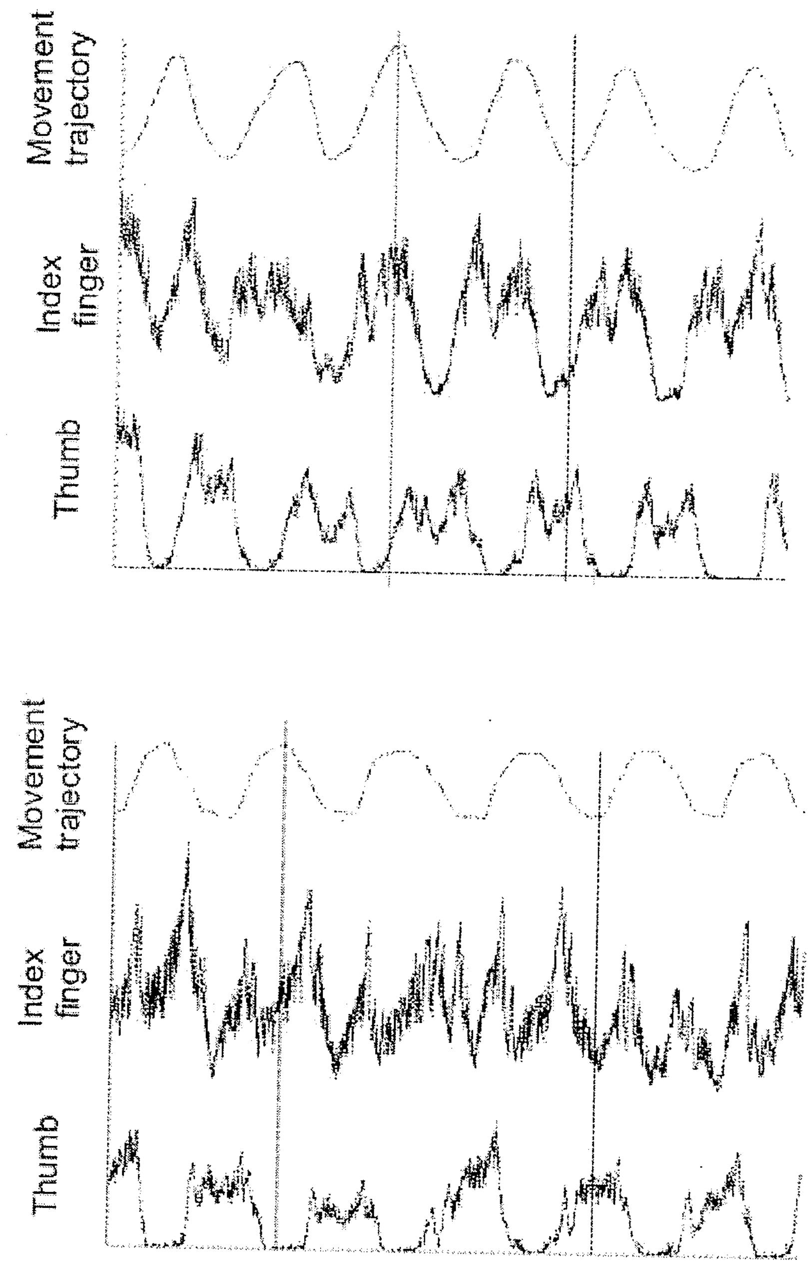
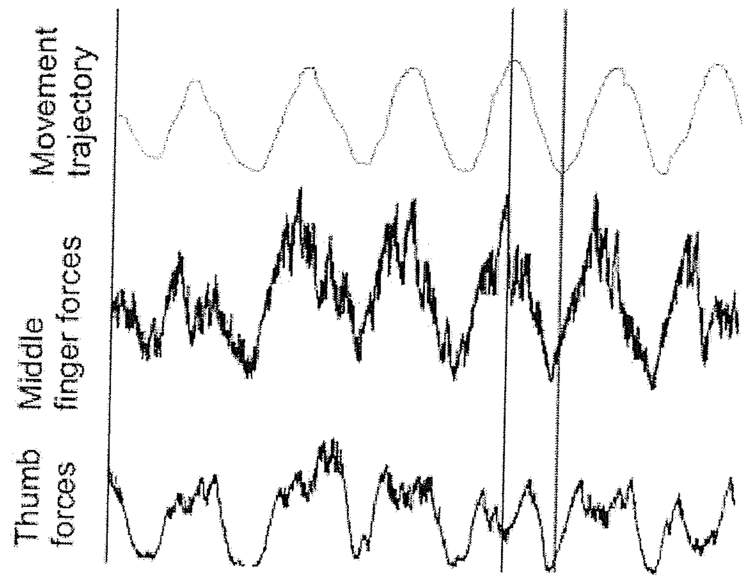


Fig 2 represent raw data for a single subject when manipulating a medium size cylinder using two finger grip (t-i). Top graph is for inverted pendulum and bottom graph is for pendulum.



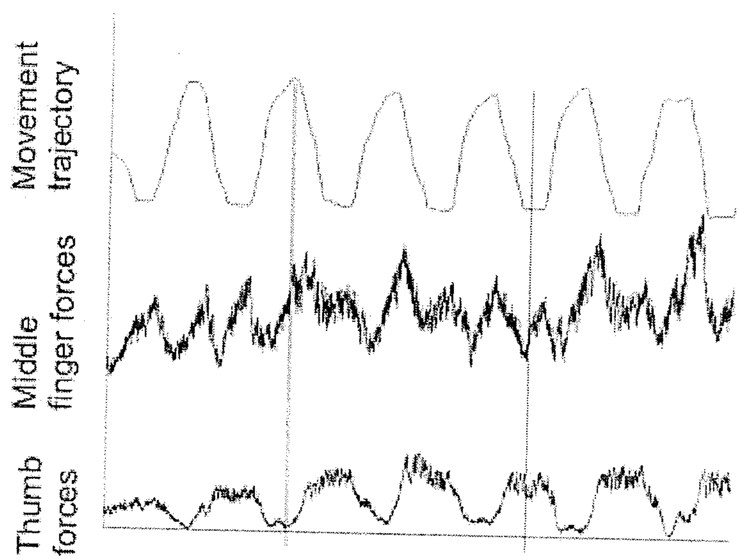


Fig 3 represent raw data for a single subject when manipulating a medium size cylinder using two finger grip (t-m).Top graph is for inverted pendulum and bottom graph is for pendulum.

Univariate Analysis

The effect of all three independent variables, i.e. grip type (3 levels), mode of manipulation (2 levels) and diameter (3 levels) was studied using repeated measures of analysis of variance (ANOVA). The summary of statistical results is shown in Table 1.

Table 1

Statistical Analysis

	Inverted Pendulum		Pendulum		Interaction Effects
	GRIP EFFECT	DIAMETER EFFECT	GRIP EFFECT	DIAMETER EFFECT	
PCC b/w target and actual movement trajectory	**$p < 0.05$ $F(2,32) = 3.82$**	N.S.	N.S.	N.S.	N.S.
PCC b/w actual movement trajectory and thumb forces	N.S.	N.S.	N.S.	N.S.	N.S.
PCC b/w actual movement trajectory and index finger forces	**$p < 0.001$ $F(2,31) = 5397.4$**	N.S.	**$p < 0.001$ $F(2,23) = 1961.82$**	N.S.	N.S.
PCC b/w actual movement trajectory and middle finger forces	**$p < 0.001$ $F(2,36) = 3683.28$**	N.S.	**$p < 0.001$ $F(2,32) = 5709.93$**	N.S.	N.S.
Phase lag b/w actual movement trajectory and thumb forces	N.S.	N.S.	N.S.	N.S.	N.S.
Phase lag b/w actual movement trajectory and index finger forces	**$p < 0.001$ $F(2,32) = 80.10$**	N.S.	**$p < 0.001$ $F(2,28) = 45.25$**	N.S.	N.S.
Phase lag b/w actual movement trajectory and middle finger forces	**$p < 0.001$ $F(2,24) = 17.75$**	N.S.	N.S.	N.S.	N.S.

	Inverted Pendulum		Pendulum		Interaction Effects
	GRIP EFFECT	DIAMETER EFFECT	GRIP EFFECT	DIAMETER EFFECT	
Temporal accuracy DiffMaxTime	N.S.	N.S.	N.S.	N.S.	N.S.
Temporal accuracy DiffMinTime	N.S.	N.S.	**$\underline{p} < 0.001$ $F(2,34) = 23.11$**	N.S.	**$\underline{p} < 0.05$ $F(2,37) = 3.922$**
RMS of thumb forces	**$\underline{p} < 0.001$ $F(2,26) = 15.10$**	**$\underline{p} < 0.001$ $F(2,38) = 11.92$**	**$\underline{p} < 0.01$ $F(2,29) = 5.64$**	**$\underline{p} < 0.05$ $F(2,37) = 5.569$**	**$\underline{p} < 0.05$ $F(2,34) = 3.63$**
RMS of index finger forces	**$\underline{p} < 0.001$ $F(2,27) = 135.34$**	N.S.	**$\underline{p} < 0.001$ $F(2,31) =100.02$**	**$\underline{p} < 0.05$ $F(2,30) = 5.714$**	N.S.
RMS of middle finger forces	**$\underline{p} < 0.001$ $F(2,23) = 112.97$**	N.S.	**$\underline{p} < 0.001$ $F(2,25) = 83.42$**	**$\underline{p} < 0.05$ $F(2,34) = 4.57$**	N.S.
Amplitude error 1^{st} peak	N.S.	N.S.	N.S.	N.S.	N.S.
Amplitude consistency	N.S.	N.S.	N.S.	N.S.	N.S.

* PCC: Peak Cross Correlation.
* N.S.: not significant

Table1. Repeated measures ANOVA to study the effect of grip type and diameter on the dependant variables in inverted pendulum and pendulum mode of manipulation. Interaction effects between mode of manipulation and grip type were studied using multivariate analysis of variance. Post-hoc comparisons were done using Tukey's test, $p < 0.05$.

Group means and SEMs for peak cross correlation coefficient (PCC) between target and actual movement trajectory are presented in Fig 4. No statistically significant effect of diameter was found on PCC in both pendulum and inverted pendulum mode. A statistically significant effect of grip type was found only in the inverted pendulum mode. Figure 4 shows that the PCC values were greater for three- than two-finger grip. The PCC values were the smallest for the two-finger grip (t-m).

Group means and SEMs for PCC between actual movement trajectory and individual finger force profiles are presented in Figure 5. No statistically significant effect of diameter was found on PCC in both modes of manipulation. A statistically significant effect of grip type was found on PCC between actual movement trajectory and middle and index finger force profiles in both modes of manipulation. In both modes of manipulation index finger force profiles were more closely related with the movement trajectory in two-finger (i) grip than to three-finger grip. For the middle finger forces profiles, in the pendulum mode the forces were more closely related with the movement trajectory in three-finger grip than to the two-finger (m) grip and in the inverted pendulum mode the forces were more closely related in two-finger (m) grip condition.

Group means and SEMs for phase lag (PL) between actual movement trajectory and individual finger forces are presented in Figure 6. Diameter had no significant effect on phase lag in both modes of manipulation. Grip had no effect on phase lag of the thumb. Grip had a significant effect on phase lag of index finger. In the pendulum mode, the PL was larger using three-finger grip. In the inverted pendulum mode, the PL was larger using the two-finger (i) grip. Grip had a significant effect on phase lag of middle finger only in the inverted pendulum mode.

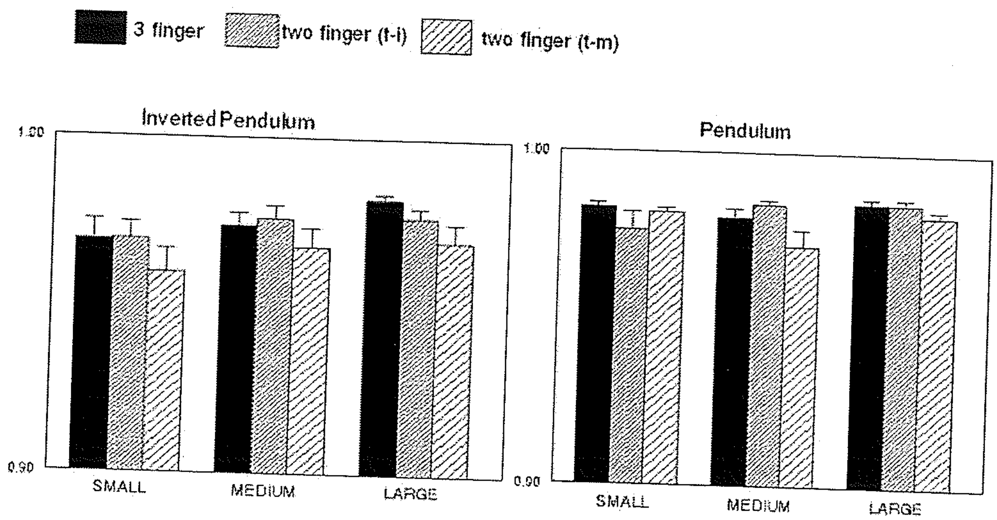


Fig 4. The graph represents group means and SEM of Peak r value between reference waveform and the actual movement waveform for each cylinder diameter and grip types (three finger; thumb-index finger; thumb-middle finger).

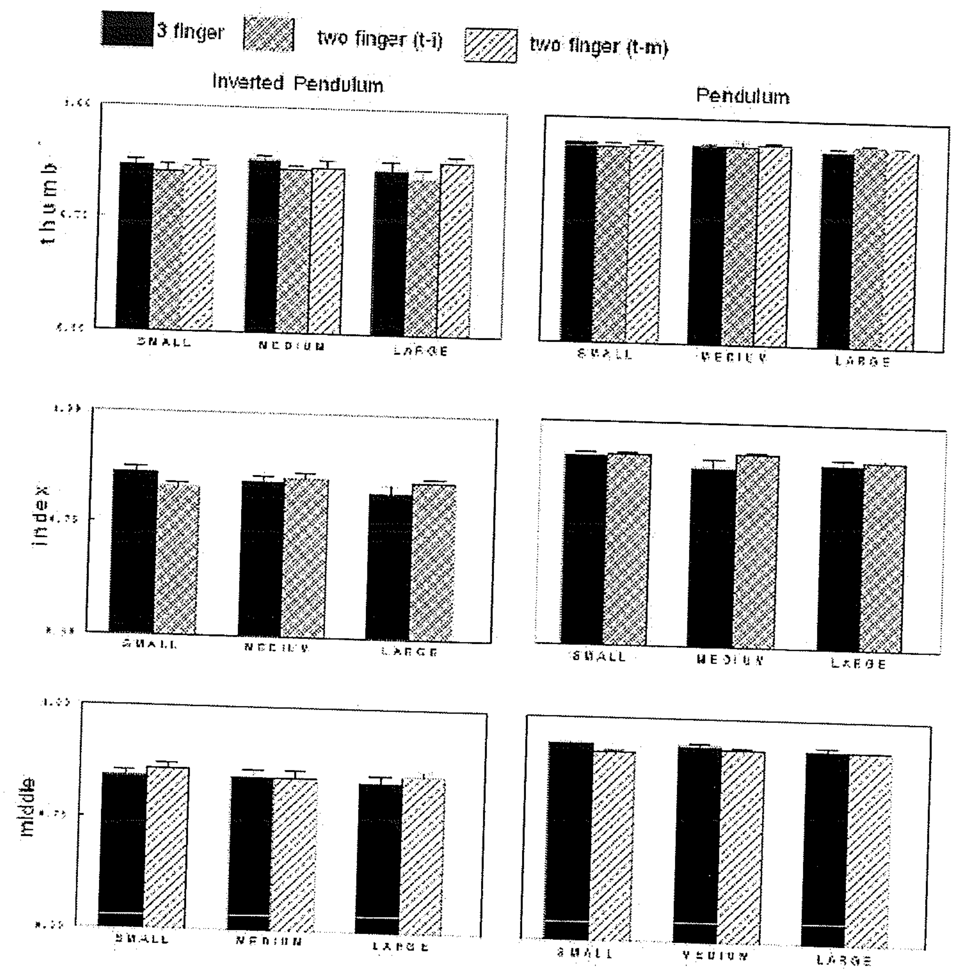


Fig 5. Group Means and SEM of Peak r value between movement trajectory and individual finger forces for each cylinder diameter and grip types. Left panel is for inverted pendulum and right panel is for pendulum.

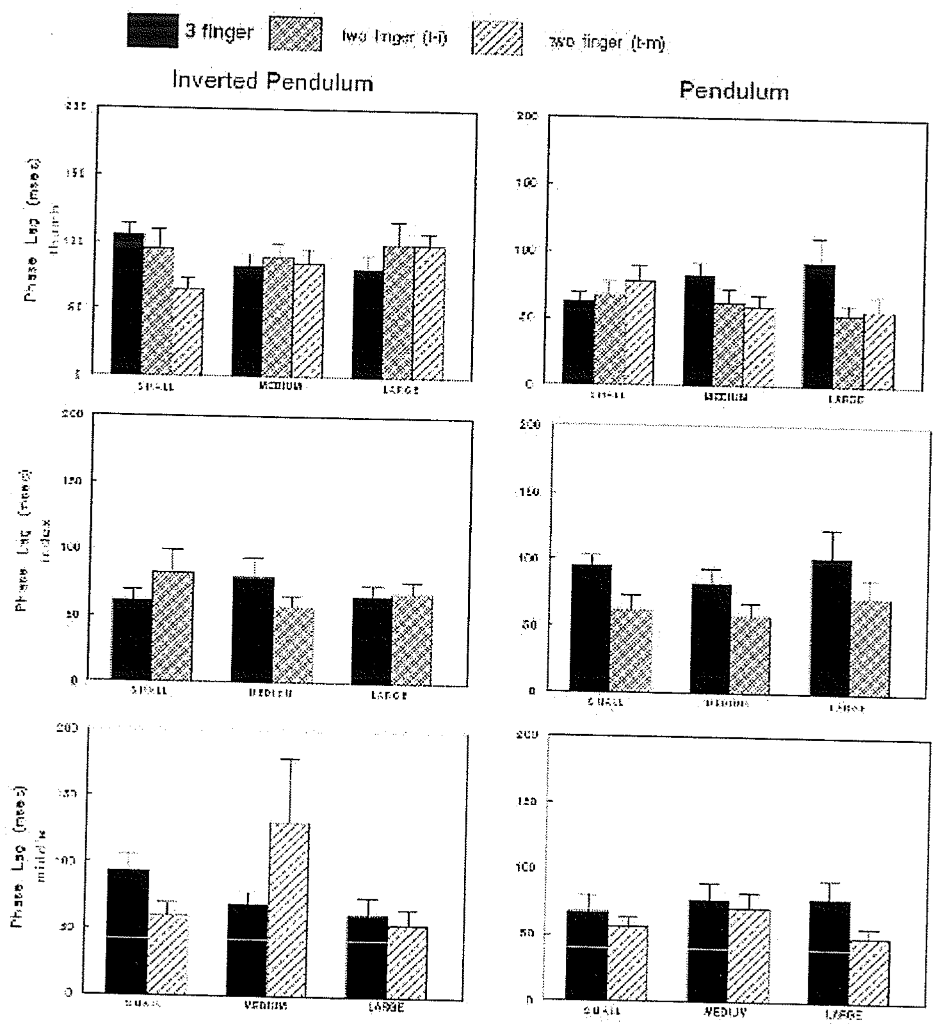


Fig:6 Presented are the group means and SEM of Phase lag between minibird and individual finger forces for each cylinder diameter and grip types. The top panel is for three finger, middle panel is for thumb and index and lower panel is for thumb and middle finger grip.

PL was larger with the three-finger than with the two-finger (m) grip.

Group means and SEMs for absolute temporal accuracy are presented in Figure 7. Diameter had no statistically significant influence on temporal accuracy in both modes of manipulation. Grip had no statistically significant influence on Diffmaxtime in both modes of manipulation. Grip had a statistically significant influence on DiffMinTime in pendulum mode. Temporal error during maximum backward movement of the object was greater using a two-finger grip (i) than a three-finger grip.

The group means and SEMs for amplitude consistency and first peak amplitude error (AE) are presented in Figure 8 and Figure 9. Diameter and grip type had no statistically significant influence on amplitude consistency in both modes of manipulation. The histogram shows a definite trend in the pattern of first peak AE (i.e. for both modes of manipulation the AE was less using three-finger grip compared to two-finger grip). However since the S.D. was more than + 2 S.D., no statistically significant results were obtained.

Group means and SEMs for RMS of finger forces are presented in Figure 10. Both diameter and grip type had a statistically significant effect on RMS of thumb forces in pendulum and inverted pendulum mode. In both modes of manipulation thumb forces were the largest during manipulation of small cylinder and the least for large cylinder. As evident from Figure 9 in the inverted pendulum mode, the RMS of thumb forces were highest using two-finger grip (m) and lowest using the three-finger grip. In the pendulum mode

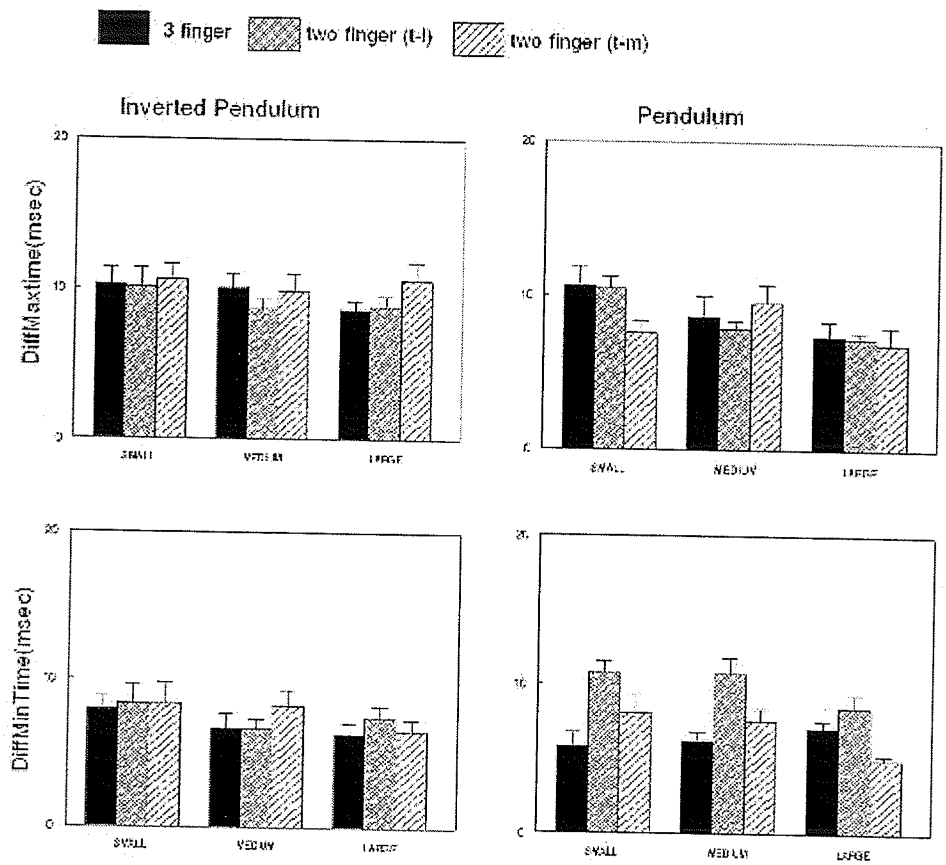


Fig 7.Presented are the group means and SEM of Temporal accuracy for each cylinder diameter and grip types (three finger; thumb-index finger; thumb-middle finger).Top panel is for diffMaxTime and the lower panel is for diffMintime.

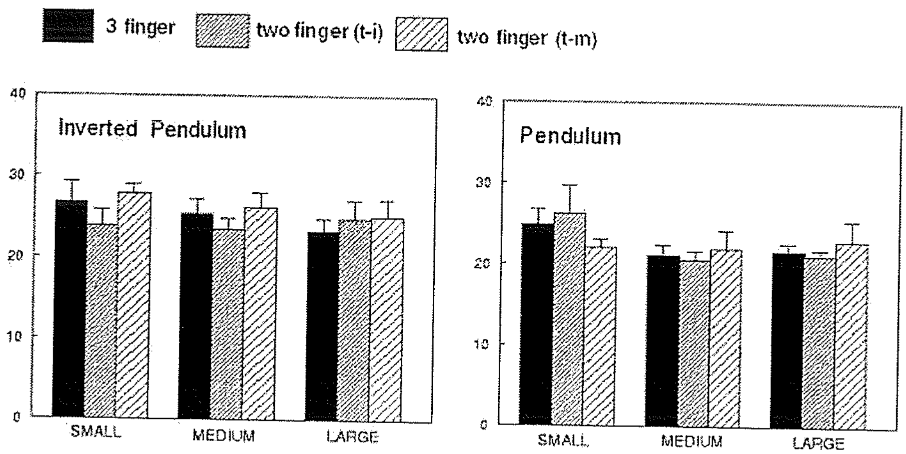


Fig 8. Presented are the group means and SEM of Amplitude consistency for each cylinder diameter and grip types (three finger; thumb-index finger; thumb-middle finger). Left panel is for inverted pendulum and right panel is for pendulum.

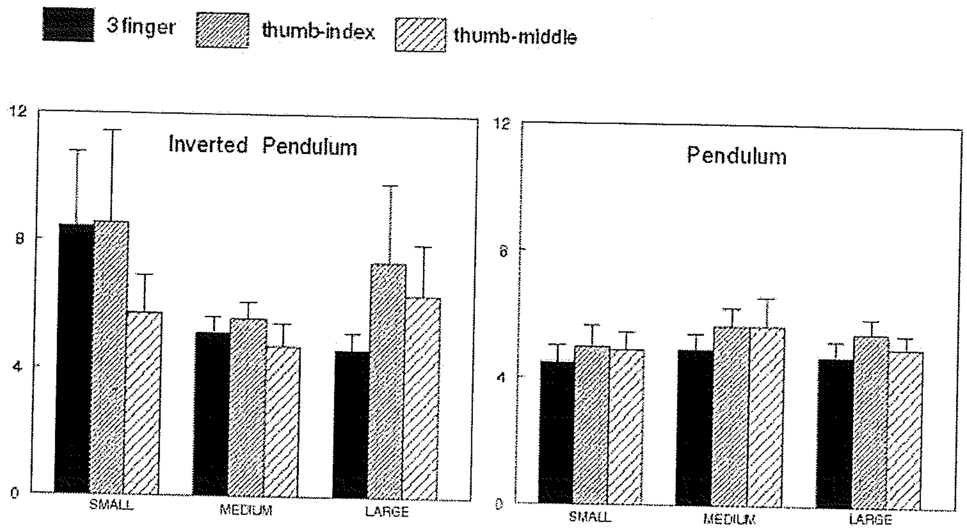


Fig 9. Presented are the group means and SEM of first peak Amplitude consistency for each cylinder diameter and grips (three finger; thumb-index finger; thumb-middle finger). Left panel is for inverted pendulum and right panel is for pendulum.

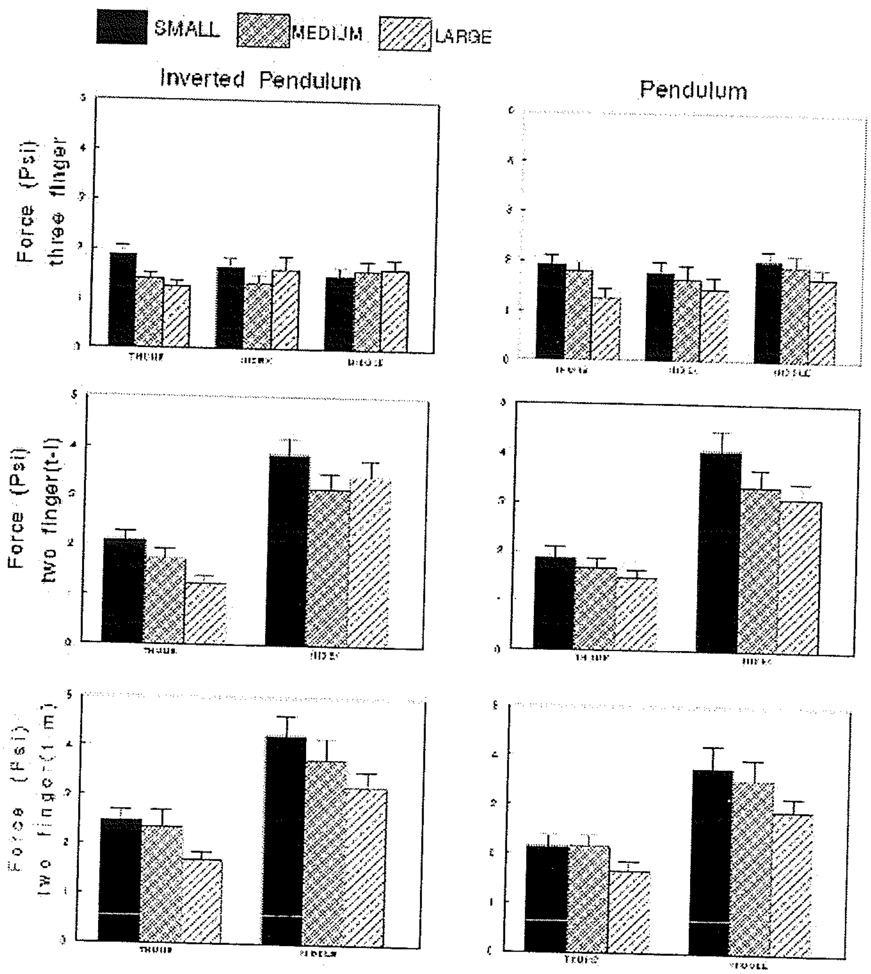


Fig:10 Presented are the group means and SEM of RMS of finger forces for each cylinder diameter and grip types. The top panel is for three finger, middle panel is for thumb and index and lower panel is for thumb and middle finger grip.

the RMS of thumb forces were highest using two-finger grip (m) and least using two-finger grip (i). Grip type had a statistically significant effect on RMS of index finger forces in both modes of manipulation. In both modes of manipulation RMS of index finger forces was higher with the two-finger grip (i) than with the three-finger grip. Diameter only had a statistically significant effect in the pendulum mode. In the pendulum mode the RMS of index finger forces were highest when manipulating a small cylinder and the lowest when manipulating a large cylinder. Grip had a statistically significant effect on RMS of middle finger forces in both modes of manipulation. In both modes of manipulation RMS of middle finger forces were higher using two-finger grip (m) than with the three finger grip. Diameter only had a statistically significant effect in the pendulum mode. In the pendulum mode the RMS of middle finger forces was the highest when manipulating a small cylinder and the lowest when manipulating a large cylinder.

Multivariate Analysis and Post Hoc Analysis

Interaction effects were studied only between grip type and mode of manipulation as diameter had no significant effect on most of the dependent variables. Post-hoc tests for ANOVA were undertaken by a Tukey multiple comparison test.

Multivariate analysis showed that there was no significant interaction effect of grip type and mode of manipulation on amplitude accuracy, phase lag and PCC. A significant interaction effect was found on RMS of thumb forces and temporal error Diffmintime. Post-hoc Tukey test for RMS of thumb forces revealed a significant interaction effect between mode of manipulation and grip type for three-finger grip ($Q(2, 51) = 18.13$ $p < .01$) and thumb and middle finger grip ($Q(2, 51) = 9.67$ $p < .01$). The thumb forces were larger using two-finger grip (m) type than three-finger grip type in both modes of manipulation. Amongst all tasks performed, the thumb forces were the largest when a two-finger grip (m) was used for manipulation of objects in inverted pendulum mode, and thumb forces were the smallest when a three-finger grip was used for manipulation of objects in the inverted pendulum mode.

There was a statistically significant difference in TE DiffMinTime between the three- and two-finger (i) grip in the pendulum mode ($Q\ (2, 76) = 4.43$, $p<0.006$). TE was much greater using the two-finger (i) grip than when using the three-finger grip. A post hoc Tukey test also revealed a significant difference in TE based on the mode of object manipulation using a two-finger (i) grip ($Q\ (2, 55) = 2.91$ $p<0.04$) i.e. TE was higher in the pendulum mode compared to the inverted pendulum mode.

Discussion

The primary aim of this study was to evaluate the effect of object curvature and grip type on movement accuracy during two modes of manipulation: a) IP where the CM was above the contact points; and b) P where the CM was below the contact points. For this purpose a visuomotor tracking of sinusoidal targets was used. Participants manipulated cylinders of various diameters (8cm, 10.5cm and 15cm) with their dominant hand while tracking a brightly colored cursor moving in a sinusoidal fashion at a fixed frequency and amplitude. The objects were weight normalized, so all cylinders weighed 50gms. The task was low precision; self paced and was produced using finger movements.

The main findings of the study were that Peak cross correlation (PCC) values between actual movement trajectory and reference trajectory were high in both IP and P modes of manipulation irrespective of grip type or diameter with one exception (i.e. PCC values were low with two-finger grip compared to three-finger grip in IP mode). A similar finding was observed for temporal accuracy measures; no effect due to grip type or diameter in IP and P modes of manipulation with the exception of decreased temporal accuracy in a two-finger grip. The present finding also showed that mean off axis movement magnitude was not influenced by diameter, grip type or mode of manipulation.

The second aim of the study was to explore the behavior of individual finger forces. The behaviour of individual finger forces required at different digits to produce/control movement was dependant upon the mode in which the object was being manipulated i.e. P or IP. The finger forces at the point of maximum forward and backward rotation of the object in the IP mode mainly served to prevent further tilt of the object and to overcome gravity to initiate rotation towards neutral. In the P mode however the finger forces during maximum forward and backward rotation of the object worked to overcome gravity to achieve movement and to ensure a smooth decent of the object towards neutral.

The study also looked at the relationship between actual movement trajectory and individual finger forces. Peak Cross correlation (PCC) between finger force profiles and actual movement trajectory was used to measure the similarity between the two signals. There was no effect of diameter or grip type on the PCC of thumb force to object motion profiles. However there was an effect of grip type on PCC of index and middle finger force profiles in both modes of manipulation. The individual finger force profiles were correlated better using two-finger grip compared to three-finger grip for all diameters in both pendulum and inverted pendulum modes of manipulation with one exception. The exception being middle finger force profiles in the pendulum mode which showed better correlation in three-finger grip compared to two-finger grip.

The average force levels exerted by individual digits during the task were significantly influenced by grip type as well as diameter in both modes of manipulation. Overall finger forces required during manipulation were highest for small cylinder and lowest for large cylinder. For all tasks performed it was found that the forces were higher for two-digit than for the three-digit grip and higher for the index or middle finger than for the thumb.

Performance of fine motor function is dependant on many factors including the frequency and velocity with which the task is performed, presence or absence of visual feedback, object size/shape, grip type and location of the object's CM relative to the point of finger contact. Most studies to date (Flanagan et al., 1999; Jenmalm et al., 1998; McDonnell, Ridding, Flavel, & Miles, 2005; Smith, 2005; Winges, Eonta, Soechting, & Flanders, 2008; Winges, Soechting, & Flanders, 2007) have examined the control of finger forces during object transport tasks where the fingers are holding the object (two or three fingers or whole hand) and the object is being moved by virtue of motion occurring at the wrist and/or elbow. It has been observed that when an object is lifted vertically or transported horizontally the forces normal to object surface increase and decrease in tandem with tangential (load) force in order to maintain a stable grip and safely avoid slips. In these hand transport tasks any transient increase in thumb-finger grasping forces is associated with object stabilization and to minimize unwanted object tilt in any direction relative to gravity (Gao, 2005; Smith, 2005; Zatsiorsky & Latash, 2004). Recent studies have observed that object stabilization during transport tasks is achieved using a hand stiffening strategy with co-contraction of extrinsic and intrinsic hand muscles. This strategy was found during horizontal translation (Winges et al., 2007) and object tilt (Winges et al., 2008). In addition it was observed that the magnitude and modulation of grasp forces and levels of co-contraction are significantly increased when the object mass centre is below the contact plane compared to when it was in the contact plane (Winges et al., 2008).

In contrast to transport tasks which involve mainly isometric and co-contraction of intrinsic and extrinsic musculature (stiffening strategy) in the present study finger rotations and flexion/extension were required to produce cyclic object tilts in two different modes of manipulation i.e. mass centre above and below point of thumb-finger contact. Thus in the present study motor control of fingers would involve coordination of object rotational acceleration/deceleration, object grasp stability (prevent slips) and minimizing unwanted off axis tilt relative to gravity. The pendular motion task would require largely concentric isotonic contractions of intrinsic/extrinsic finger muscles. The inverted pendular tasks would require both concentric and eccentric isotonic contraction of intrinsic/extrinsic finger muscles (i.e. to control object tilt away from vertical and to produce tilt against gravity). A hand stiffening strategy with largely isometric finger muscle contractions could not be used for these types of precision object manipulations.

The findings of this study showed that performance was not challenged by diameter or grip type in the pendulum mode. However a decline in performance was observed when two-finger grip was used in the inverted pendulum mode. The finger forces used in a two digit grip were higher than a three digit grip. Further, larger phase lags were seen with two-finger grip than three-finger grip for index finger force profiles in IP mode. Thus by altering location of mass centre (above versus below the contact point) and by reducing the number of fingers used the task difficulty was increased as indicated by a reduction in the performance measures, larger phase lags and the need for larger contact force levels. Thus when evaluating functional tasks, difficulty of the goal, type of grip and object physics will all impact performance. During a pendular motion the object (mass centre) is subject to a gravitational restoring force that will accelerate it towards its vertical position. Hence when the pendulum is displaced from its place of rest, the passive restoring force will cause the pendulum to oscillate about the vertical position and this will reduce the finger forces required to produce and guide the pendular motion.

In contrast, for IP, the restoring forces are not present and gravity is tilting the object away from the vertical. In addition, with a three-finger precision grip there is larger contact area between the fingers and the object and this provides increased afferent input from the fingers which facilitates a more accurate estimation of task performance, (Kjnoshita, Kawai, & Ikuta, 1995). A larger contact area with three-finger grip also results in greater friction between fingers and the object and this improves stability (Aoki, 2007; Burstedt et al., 1999; Cadoret & Smith, 1996). With a three-digit grasp, it is possible to reposition the digits to establish different grasp configurations as the object is tilted away from the vertical and to disengage a digit to be used in tactile exploration or stereognostic tasks (Flanagan et al., 1999). Thus a three-finger grip for manipulation of objects with CM above the finger contact appears more functional.

Correlation between Individual Finger Forces and Actual Movement Trajectory

The present study found that both index and middle finger contact forces were more closely related to the object orientation (tilting movement) using two-finger grip type than with a three-finger grip type with one exception: middle finger force profiles in pendulum mode.

In a two-digit grip, the thumb-finger combinations produced motion, stabilized object and minimized off axis tilt. For the thumb and index finger grip, in both the IP and P mode the thumb force profiles were maximum during backward rotation of the object and the index finger force profiles were maximum at the forward rotation of the object (Figure 2). Thus for the thumb-index grip, the thumb and the index finger forces were stabilizing the object at the backward and forward maximum tilt positions of the object respectively. For the thumb and middle finger grip in the IP mode, the finger contact forces for both the thumb and middle finger were maximum at the forward rotation of the object (Figure 3). The data also revealed that middle finger forces decreased as the backward rotation of the object started yet were always an order of magnitude larger than the thumb forces even at the end of backward rotation. This leads us to believe that the middle finger forces were working to stabilize the object at either end of rotation as well as to initiate the backward to forward rotation of the object.

With the three-finger grip, the PCC values between finger forces and the movement trajectory were low. In addition, the middle and the index finger force profiles increased and decreased in opposite direction to each other. Larger phase lags between individual fingers (i.e. index and middle) and movement trajectory were observed using a three-finger grip.

Arbib, Iberall, and Lyons (1985) proposed the virtual finger hypothesis, where objects were grasped by using the thumb and virtual finger acting in opposition. The virtual finger was represented by the weighted summed action of two or more fingers in such a manner as to oppose the force vector of the thumb and thus hold and stabilize the object. Baud-Bovy and Soechting (2001) evaluated the virtual finger hypothesis during a vertical lifting task. The manipulandum in this study had three flat surfaces and was held using a three-finger grip; the lift was performed by elbow flexion. They found that the direction of the force exerted by the thumb did not depend on the orientation of the surfaces contacted by the two fingers. Rather, the thumb forces were directed midway between the two finger contact points. They observed that the directions of the individual finger forces were mirror symmetric about this axis, and that the vector sum of the index and middle finger forces acted to oppose the thumb force vector. Thus for vertical lifting movements with minimal object tilt the tripod grasp used to hold an object did satisfy the virtual finger hypothesis. These findings have been extended to circular objects by Gentilucci (2003); Winges et al. (2008); Olafsdottir, Zatsiorsky, and Latash (2005). The findings with the three-finger grip are not in agreement with the virtual finger hypothesis. The decreased PCC values with three-finger grip suggest that no one finger was responsible for the forward or backward rotation of the object. Based on the virtual finger hypothesis it would be expected that the index and middle finger forces work together to produce desired object tilt and maintain object stability (Flanagan et al., 1999). However in both IP and P mode the index and the middle finger force profiles were in the opposite direction to each other and the thumb and middle finger force profiles exhibited the same pattern and direction (Figures 1a and 1b). In a study done by Sharp and Newell (2000) showed a strong relation between the thumb and middle finger forces in an isometric voluntary contraction task. In the IP mode the middle finger and the thumb produced forces that increased in magnitude with the forward movement of the object whereas in the P mode the forces increased with the backward movement of the object. The index finger force profiles were similar in pattern and opposite in direction to the thumb and middle finger forces in both the IP and P mode.

In the pendulum mode the middle finger forces were more closely related to the movement trajectory in a three-finger grip compared to a two-finger grip. In the pendulum mode since restoring forces are present and are assisting in regaining an equilibrium position the need for two fingers opposite the thumb seems redundant. In this study the middle finger forces were in phase with the backward rotation of the object. The thumb and the index finger, acting in opposition, acquired the role of object stabilization. Hence the middle finger forces were solely responsible for producing the backward rotation and hence the close correlation with the movement trajectory. In a two- digit grip (t-m) the middle finger has to produce movement as well stabilize the object against the thumb. For the thumb and middle finger grip the middle finger was consistently firing through out movement of the object and cyclic movement pattern was much less evident in the finger force profiles (Figure 3).Thus for the P mode it may be that the middle finger is able to produce sufficient forces to both counteract the thumb forces and produce movement and the index finger is actually interfering with movement although it might be stabilizing the object and preventing slip.

One possible explanation for the findings in this study is that since the fingers were responsible for producing the movement as well as stabilizing the object against slips and off axis rotation, the strategy used differed from the virtual finger hypothesis. During the object tilting task, the thumb forces were essential to initiate forward rotation and the index /middle finger were essential to initiate backward rotation of the object. During object transport tasks the fingers are essentially performing the function of holding onto the object hence the demands are one fold i.e. stabilization.

Effect of Object Curvature and Grip Type on RMS of Finger Forces

Jenmalm et al. (1998) studied the effect of surface curvature during a lift and hold task, where the manipulandum was held using thumb and index finger and lifted vertically by elbow flexion. The authors found that surface curvature had no effect on the magnitude of the grip forces. In a subsequent study by Goodwin et al. (1998) the authors evaluated the effect of surface curvature on grip forces during a task where the object was tilted. The instrumented object was held using two-finger grip and tilted using a combination of elbow flexion and wrist radial deviation. The authors found that surface curvature had a profound effect on thumb and index finger forces under torque loads. As the surface curvature increased, so did the grip forces (i.e. larger forces were required for the smaller object diameter than for an object with a larger diameter). Similar findings were also found by Goodwin et al. (1998); Goodwin et al. (1998) and Jenmalm et al. (2000). This study extends these findings to actual finger manipulation tasks. In the present study the mean grip forces were found to be higher for the small diameter compared to large diameter for all experimental conditions. This is consistent with the above results.

Another possible explanation for increase force levels with small diameter objects may relate to the change in surface area of contact and not necessarily force production. With a large diameter object there is more finger contact area than there is with objects with smaller diameter and based on the physical relationship of forces per unit surface area, the same force applied over a smaller surface area appears larger. Hence for objects with large diameter the contact forces are distributed over a wider area; for smaller diameters the contact forces are concentrated in a smaller area. It should be noted that larger contact area also means greater friction and reduced chances of slip.

The study also revealed that regardless of the type of grip used or the object diameter, the mean thumb forces were less than the mean index or middle finger forces. The muscles of the thumb have been identified as more highly correlated with low levels of force production and with force modulation, as compared to the muscles of the index finger (Kilbreath & Gandevia, 1993; Maier & Hepp-Reymond, 1995). The authors showed this during a task where the subjects matched a reference weight lifted on the right with a variable weight lifted on the left by the same muscle. In a study by Li, Latash, Newell, and Zatsiorsky (1998), the authors found that the mean grip forces employed by the index/middle finger were almost double in magnitude using two-finger grip than with the three-finger grip. This is again explained on the basis of stability principle and larger surface area contributing to greater digit-object friction and greater dissipation of forces.

Conclusion

Everyday tasks require precise manipulation of objects. Successful manipulation requires an increase and decrease in grip forces such that no slip occurs and the desired goal is achieved. The behavior of finger forces during transport and manipulation tasks has been an area of interest for researchers for many decades. Extensive work has been done to understand finger forces during arm movement tasks and static hold tasks. This study is intended to expand the current literature. Finger force profiles and movement accuracy were examined in tasks that were primarily performed using finger movements. This study revealed that objects measuring 8cm to 15cm in diameter and weighing 50 gms, can be manipulated using a two or three-finger grip without compromising movement accuracy as long as there are no significant torque challenges (pendulum mode). However when manipulation was performed under increased torque loads (inverted pendulum) the performance declined using two-finger grip. Thus a three-finger grip offers better movement accuracy and is also more economical in terms of mean forces used when manipulating objects with the centre of mass above the point of contact of the fingers.

The study also concludes that for finger manipulation tasks the interaction between individual finger forces depends on the size of the object (diameter) and on the demands posed by the task.

Future Implications

1. It is important to have a direct measure that can explain the role of virtual finger hypothesis in tasks performed primarily with finger movements. In future studies an analysis to look at the summed version of the finger force profiles may provide better understanding of how the summed version relates to the thumb forces and to the time varying motion.
2. Frequency analyses in future studies may enable us to view object instabilities and role of feedback processes in predictable rhythmic visuo motor tracking tasks performed using precision grip.
3. Objects of diameters up to 15cm were used in this study. Since many of the objects used in everyday life measure more than 15cm in diameter it may be beneficial to look at effect of grip type on larger diameters, to understand when it becomes essential to change from a 2 to 3, 3 to 4 and 4 to a whole hand grip.
4. In our study the movement was predictable and so most of the potential torque loads were also predictable. However many everyday activities demand stability under unpredictable conditions. It may be interesting to see how the above findings change when there is a moment to moment change in external torques.

Limitations of the Study

1. A sample of convenience consisting 20 healthy subjects was recruited for this study. In order to be able to study the peak cross correlations among various dependent variables it is necessary to have a larger sample size in order to avoid a Type 1 error.
2. In future studies, recording the exact location of finger placement on the object will provide better understanding of changing grip mechanics as a function of diameter.

References

Aoki, T. (2007). Adjustments to local friction in multifinger prehension.

Arbib, M. A., Iberall, T., & Lyons, D. (1985). Coordinated control programs for movements of the hand. Exp.Brain Res.Suppl 10, 111-129.

Ref Type: Generic

Armbruster, C. & Spijkers, W. (2006). Movement planning in prehension: do intended actions influence the initial reach and grasp movement? *Motor Control, 10,* 311-329.

Ballard, D. H., Hayhoe, M. M., Li, F., & Whitehead, S. D. (1992). Hand-eye coordination during sequential tasks. *Philos.Trans.R.Soc.Lond B Biol.Sci., 337,* 331-338.

Baud-Bovy, G. & Soechting, J. F. (2001). Two virtual fingers in the control of the tripod grasp 1. *J Neurophysiol., 86,* 604-615.

Baud-Bovy, G. & Soechting, J. F. (2002). Factors influencing variability in load forces in a tripod grasp. *Exp.Brain Res., 143,* 57-66.

Burstedt, M. K., Flanagan, J. R., & Johansson, R. S. (1999). Control of grasp stability in humans under different frictional conditions during multidigit manipulation. *J.Neurophysiol., 82,* 2393-2405.

Cadoret, G. & Smith, A. M. (1996). Friction, not texture, dictates grip forces used during object manipulation. *J.Neurophysiol., 75,* 1963-1969.

Carey, J. R., Greer, K. R., Grunewald, T. K., Steele, J. L., Wiemiller, J. W., Bhatt, E. et al. (2006). Primary motor area activation during precision-demanding versus simple finger movement. *Neurorehabil.Neural Repair, 20,* 361-370.

Carey, J. R., Kimberley, T. J., Lewis, S. M., Auerbach, E. J., Dorsey, L., Rundquist, P. et al. (2002). Analysis of fMRI and finger tracking training in subjects with chronic stroke. *Brain, 125,* 773-788.

Carey, J. R., Patterson, R., & Hollenstein, P. J. (1988). Sensitivity and reliability of force tracking and joint-movement tracking scores in healthy subjects. *Phys.Ther., 68,* 1087-1091.

Colebatch, J. G. & Gandevia, S.C. (1989). The distribution of muscular weakness in upper motor neuron lesions affecting the arm. *Brain, 112 (Pt 3),* 749-763.

Cutkosky, M. R. (1989). On grasping choice, grasping models, and the design of hands for manufacturing tasks. IEEE Trans.Robotics and Automation 5[3], 269-279.

Ref Type: Generic

Desmurget, M., Prablanc, C., Arzi, M., Rossetti, Y., Paulignan, Y., & Urquizar, C. (1996). Integrated control of hand transport and orientation during prehension movements. *Exp.Brain Res., 110,* 265-278.

Doyon, J., Song, A. W., Karni, A., Lalonde, F., Adams, M. M., & Ungerleider, L. G. (2002). Experience-dependent changes in cerebellar contributions to motor sequence learning. *Proc.Natl.Acad.Sci.U.S A, 99,* 1017-1022.

Ehrsson, H. H., Fagergren, A., Jonsson, T., Westling, G., Johansson, R. S., & Forssberg, H. (2000). Cortical activity in precision- versus power-grip tasks: an fMRI study. *J.Neurophysiol., 83,* 528-536.

Fagergren, A., Ekeberg, O., & Forssberg, H. (2003). Control strategies correcting inaccurately programmed fingertip forces: model predictions derived from human behavior. *J.Neurophysiol., 89,* 2904-2916.

Flanagan, J. R., Burstedt, M. K., & Johansson, R. S. (1999). Control of fingertip forces in multidigit manipulation. *J.Neurophysiol., 81,* 1706-1717.

Flanagan, J. R. & Wing, A. M. (1993). Modulation of grip force with load force during point-to-point arm movements. *Exp.Brain Res., 95,* 131-143.

Flanagan, J. R. & Wing, A. M. (1997). The role of internal models in motion planning and control: evidence from grip force adjustments during movements of hand-held loads. *J Neurosci., 17,* 1519-1528.

Gao, F. (2005). Internal forces during object manipulation.

Gentilucci, M. (2003). Finger control in the tripod grasp.

Ghez, C., Hening, W., & Gordon, J. (1991). Organization of voluntary movement. *Curr.Opin.Neurobiol., 1,* 664-671.

Gonzalez-Alvarez, C., Subramanian, A., & Pardhan, S. (2007). Reaching and grasping with restricted peripheral vision. *Ophthalmic Physiol Opt., 27,* 265-274.