Effect of Fluid Motion on Movement Performance and Finger-force Pattern during Manipulation of Containers/cups Filled with Liquid

by

Kalpana Ravala

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE

School of Medical Rehabilitation

University of Manitoba

Winnipeg

ABSTRACT

The purposes of this study were to: 1) evaluate how movement performance of the thumb and fingers were modified during manipulation of objects with and without fluids and 2) to quantify movement performance and accuracy during manipulation of objects, in two different modes of manipulation, i.e., pendulum and inverted pendulum. Twenty young healthy adults (age 24-35) were recruited and performed two predictable cyclic tracking tasks and episodic short-duration precision movement task. No change in movement performance observed in open-loop or episodic tasks. However, in closed-loop task, mode of manipulation (IP versus P) had a significant effect on amplitude consistency ($P<0.001$), and temporal accuracy ($P<0.050$).Fluid motion had a significant effect on RMS of index finger contact forces ($p < 0.01$) in episodic task. In conclusion, fluid motion had no significant effect on movement performance and accuracy.The quality of movement was better in pendulum mode than inverted pendulum movement.

ACKNOWLEDGEMENTS

One of the most important rewards in pursuing a M.Sc. degree is to be associated with intelligent and helpful minds. I am most fortunate and grateful in this regard. First of all, I would like to thank my Professor Dr. Tony Szturm, my academic supervisor, who has contributed to all aspects of my academic Endeavour. He introduced me to this challenging discipline of Motor Control in Hand, motivated me to conduct original research with high standards and supervised the entire thesis research at all levels. I am sincerely grateful for his effort in training me to become a successful researcher. His dedication to work, perfectionism and decency will have a far reaching impact on my life, academic and beyond.

I am also very grateful to the rest of my supervisory committee members: Professor Dr. Barbara Shay and Dr. Bertram Unger who served as internal and external examiners of this thesis.

I am also very grateful to my parents Mr. Nageswara rao and Mrs.Anjana devi and my brother Nanda kishore who always motivated me to reach carrier heights. Successful completion of this work would never be possible without their constant support and encouragement.

I specially thank my friend Mr. Sai Prasad Pydi and my colleague Dan Lockery for their technical support. Last but not the least; I thank all my fellow graduate students and

friends for their contributions to my work.

DEDICATION

My deepest and warmest thanks go to my parents, Mr. Nageswara Rao Ravala and Anjana Devi Ravala, whose love and support has kept me going. I express my heartfelt gratitude and affection to my parents to whom I dedicate this thesis.

Kalpana Ravala

Winnipeg, 2011

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE LEGENDS

LIST OF TABLES

ABBREVIATIONS

GF: Grip force

LF: Load force

COM: Center of Mass

IP: Inverted pendulum

P: Pendulum

MCC: Maximum Cross-correlation

FSA: Foot Insole Pressure Mapping System

RMSE: Root Mean Squared Error

INTRODUCTION

Successful object manipulation requires the selection of motor commands tailored to the manipulative intent, the task at hand, and the relevant physical properties of the manipulated object. For instance, most tasks require that we stabilize the object within our grasp as we move the object or use it as a tool. To prevent slips and accidental loss of the object, we must apply adequately large forces normal to the grip surfaces (grip forces) (Jenmalmetal., 1997**)** in relation to destabilizing forces tangential to the grip surfaces (load forces) (Jenmalmetal.,1997**)** i.e.; The force which opposes an effort force. At the same time, excessive grip forces must be avoided because they cause unnecessary fatigue and may crush fragile objects or injure the hand. Hence, the term *grasp stability* entails prevention of accidental slips as well as excessive fingertip forces.

To be successful, precise manipulation of common daily objects requires the coordination of forces exerted on the object by the tips of the fingers and thumb. This has largely been studied by examining fingertip forces during a simple grasp, lift, and hold paradigm where wrist or elbow motion produces object motion. During the lifting and subsequent holding, the magnitude of grip force is adjusted to the object's physical properties, i.e., key ones are due to mass and inertial forces, and these are often grouped into one term, *load force*. The control of grip and load forces in object manipulation involves interplay between two types of physiological controls. This involves both feed-forward control, based on prediction, and feedback control that deals with movement errors or slips and for movement errors and unpredictable external disturbances.

The majority of studies to date have evaluated movements and modulation of contact forces either during the hold phase of vertical lifting tasks or during slow vertical/horizontal object translation where the primary motion occurs at the elbow joint or wrist. The thumb and fingers are used to grasp the object and prevent it from slipping, i.e., it is a grasping action. There is a need to extend this information to understand factors governing spatial and temporal accuracy and contact force regulation during dynamic object manipulation tasks where motion of the digits are producing and controlling the object motion. Another area that needs more attention is the examination of motor control during precision manipulation of irregular-shaped objects or objects with variable mass centre locations.

Pouring fluids from one container into another or into ones mouth is one of many challenges facing individuals with neurological and musculoskeletal disorders/injuries. Objects that contain fluid pose a unique feature in that, as the object is tilted, the fluid and the object mass centre move. With larger objects like a water bottle or juice drink, the fluid movement is often unpredictable, and thus, timely tactile sensory feedback and rapid corrective movements are required to prevent slips and unwanted spills.

The primary aim of this study was to examine the effects of moving center of mass (COM) due to fluid flow on movement accuracy and performance of fine motor skills involving goal-directed object manipulations where fingers are producing the motions.

LITERATURE REVIEW

1. Physiology involved in Object Handling and Manipulation

In object manipulation, both sensory and perceptual information are critical for precise motor control of the hands. Vision provides critical predictive information for feed-forward processing of object coordinates in space and some aspects of object shape, weight, and texture. This information is transformed into movements of the hand and pre-shaping of fingers to accommodate object shape. Once the object is grasped, the cutaneous tactile sensors and muscle proprioceptors provide essential feedback information for the timely, accurate manipulation of the object.

Jenmalm and Johansson (1997) examined the relative importance of visual versus digital afferent information for the adaptation of the fingertip forces to object shape while participants lifted a test object about 5 cm above its support by means of elbow/shoulder muscles, i.e., grasping action.

All participants used vision to identify which of the three object shapes were presented (corresponding to -30, 0, and 30° surface angles) and then retrieved information about the required finger forces from memory of previous lifts with these specific shapes. The participants adapted their fingertip forces to the current new surface angle by adjusting to a smaller angle when they lifted the object tapered downward (-30°) after a change from an upward-tapered shape (30°) and vice versa. As there was same coordination between the horizontal force and the vertical force was maintained throughout all trials of each block, it was evident that there was no learning involved during a block of trails. These findings strongly suggest that participants used visual information about object shape in a feed-forward manner in adapting fingertip forces prior to object contact.

However, when the participants were blindfolded, an adjustment of the force coordination to the new angle began after 70 to 90 ms.When the object was touched in the absence of vision, these adjustments of fingertip forces to object shape were thus mediated through somatosensory information. The behavior in sighted participants (with vision) whose digits were completely anaesthetized further indicated that vision controls the adjustments of fingertip forces to object shape in a feed-forward manner. Compared with normal digital sensibility, the participants used considerably stronger horizontal forces throughout the trials without digital sensibility. But without vision and somatosensory inputs, the performance was severely impaired.

In summary this study has shown that both vision and somatosensory inputs can be used in conjunction with sensorimotor memories in adjustment of the force coordination to object shape during grasp (Jenmalm et al., 1997). Although visual information about object properties may be helpful in terms of force selection, ultimately people adapt to such constraints by using sensory information provided by digital mechanoreceptors once the object is contacted.

2. Feed-forward and Feedback Control

Voluntary movements improve with practice as one learns not only to reduce errors but also to anticipate and correct for environmental events and obstacles that perturb the body. The nervous system learns to correct for such external perturbations in two ways:

1. It uses the same or different senses (e.g., vision, hearing, touch) to detect imminent events and perturbations and initiate proactive strategies based on experience. This

anticipatory mode is called feed-forward. Kandel et al., (2000)

2. It monitors sensory signals and uses this information to act directly on the limb itself. This moment-to-moment control is called feedback. Kandel et al., (2000)

Feed-forward control

The nervous system uses vision or touch to detect the disturbances and initiates a plan of action to achieve a particular goal based on experiences. This anticipatory mode is called feed-forward control. The feed-forward process controls and estimates the future state of the motor system. It proposes that a motor command is defined well in advance before the onset of movement. In response to a desired task or trajectory, this process generates the signals required to produce the joint torques and forces used to control a movement.

Flanagan and Wing (1993) studied how grip force is modulated when participants were asked to move an object while the properties of the object were kept constant. When a grasped object is moved, a force (proportional to acceleration) must be applied to overcome its inertia. The question was how grip force was modulated during arm movements to cope with changes in load force induced by the movement and which mechanisms were responsible. They investigated the relation between change in grip force and load force during vertical and horizontal arm movements of varying rate and direction. Participants moved a cylindrical force transducer of 0.26 kg with precision grip and were instructed to make upward and downward movements at either a moderate rate or a faster rate to make fairly large-amplitude movements from 20 to 40 cm. By varying movement rate, the amplitude of inertial load modulation was manipulated.

Times to grip force and load force peaks were calculated relative to the start of the movement. The force in the direction of movement was obtained by multiplying the measured acceleration of the object by its mass. In the case of horizontal movements, this force is purely inertial. However, in the case of vertical movements, the force in the direction of movement or vertical force is the sum of the inertial force and the force due to gravity (i.e., the weight of the object).

The results of this experiment show that the grip force and load force maxima and minima closely coincided in time. In both vertical and horizontal movements, grip force increased during the movement in anticipation of load force. The changes in grip force anticipate fluctuations in inertial force (and hence, load force) that result from arm movements with a hand-held mass. In both acceleration and deceleration phases, the timing of maximum grip force coincided with timing of maximum load force, i.e., at 0.2 seconds. This was true for both slower and faster movements. Therefore, this close temporal coupling shows that the grip force changes are anticipatory in relation to the changes that are taking place in load force. This close relationship was also observed in the first movement made by each subject using lifting task, which clearly implies the presence of feed-forward control. If the subjects were using feedback control strategy, there would have been measurable delays between the increase or decrease in load force measured at the hand and the corrective adjustments in grip forces. The grip force is programmed in advance of voluntary manipulations of mechanically predictable objects. Thus, not only do grip force adjustments anticipate environmental demands imposed by the properties of the object, they also anticipate the consequences of our own actions changes.

Wing and Lederman (1998) conducted a study to determine whether grip force increases would coincide with the onset of load torques, indicating that they are anticipatory, or whether grip force changes would follow load torques at an appreciable delay, indicating that they are feedback driven. Participants were asked to make a brisk movement of the hand from right to left in a frontoparallel plane while holding a cylindrical force transducer of 0.26 kg. A fixed sequence of grasp positions were used corresponding to COM moment arms of 0, 30, 45, and 60 mm. The acceleration traces shows that the movement lasted approximately 400 ms. The traces confirm that grip force rose with, or slightly before, the rise in acceleration. Maximum grip force was clearly greater for larger values of the COM moment arm. Participants clearly increased their grip force with an increase in moment arm, $p < .01$. The differences between grip force functions in the four conditions were apparent relatively early, within 100 ms of movement onset. The peak rate of change of grip force occurred on average 52 ms after movement onset. The results of this experiment show that, when participants moved an object held in precision grip, they modulated grip force in parallel with or slightly ahead of movement. At any given grasp position, peak grip force and peak rate of change of grip force were correlated with peak acceleration. Peak grip force and peak rate of increase of grip force were scaled according to the size of the COM moment arm and hence to the inertial torque that is developed by horizontal acceleration and deceleration of the hand. The grip force began to rise before the onset of acceleration. Moreover, the peak rate of change of grip force is sufficiently early after movement onset that it is not likely to have been affected by feedback. Hence, these grip force adjustments are anticipatory and reflect participants' efforts to prevent the object from swinging in their grasp, Wing and

Lederman (1998).

Wing and Lederman (1998) also examined grip force adjustments in lifting an object using a COM-offset grasp position similar to those associated with transporting the object. Participants raised the apparatus 10 to 20 mm above the surface of the support while attempting to keep it horizontal for a period of 2 to 3 sec .Peak grip force, peak rate of change of grip force, and angle, change as a function of COM moment arm. There were significant effects of moment arm on grip force, $p < .01$, grip force rate, $p < .01$.Thus, these results show that participants also adjust grip force , and grip force rate, in anticipation of inertial torque in lifting.

When participants were asked to use grasp points creating a greater COM moment arm, they increased the grip force they used to stabilize the object in the hand. Moreover, the peak rate of rise of grip force, occurring early after the onset of load force and torque, was matched to the COM moment arm, and hence to the torque produced by a given level of acceleration. This tailoring of peak rate of grip force to moment arm strongly suggests advance setting of grip force levels according to anticipated load torque because the time delay following movement onset was so short that it is unlikely that the adjustment could have been set by feedback following the onset of load force and torque .Wing and Lederman (1998).

Winges et al. (2007) examined how changes in the inertial properties of an object affect the grasp during horizontal transport. Participants were asked to grasp a manipulandum (cylindrical object consisted of two parallel grip surfaces (30 mm diameter), spaced 25 mm apart.) with their right hand using a tripod grasp, lift it, and respond to a tone by quickly moving it 20 cm horizontally from the center point to one of eight targets equally spaced on a perimeter (center-out). Position data were differentiated to obtain velocity and acceleration of the object during the movement. Movement onset and end were determined as the points when movement speed was 5% of the maximum speed for that movement. Force and position data were then time normalized to 100% of the movement duration. Results of this experiment showed that grasp forces had an effect during object transport. This increase of grasp forces was aimed at stabilizing object orientation during translation. When the COM was fixed below the contact plane, resulting in the generation of predictable external torques, the amplitude of grasp force increased. When the COM was located within the contact plane, the small moments that occur during horizontal transport likely arose from vertical offsets of the three contact points. However, when the center of mass was below the contact plane, larger moments occurred during movement, thus increasing the forces needed to stabilize the object. Therefore, the modulation of internal grasp force during the movement was related to stabilization of the object, and this modulation was affected by the location of the center of mass. Furthermore, when the center of mass is at a fixed point, either within or below the contact plane, a feed-forward strategy could be used to successfully perform the movement while stabilizing the object orientation because the external moments would be predictable with respect to acceleration (Winges et al., 2007).

In another experimental condition, more complex moments were introduced by allowing the low center of mass to swing around a pivot point. Because the pendulum condition resulted in complex external torques, if grasp force was modulated based on sensory feedback, the effect of the pendulum should have been apparent in the electromyography (EMG) with a lag. However, regression analysis revealed no consistent relation between the pendular motion and muscle activity, even though the effect of the pendulum was apparent in the forces at each digit. EMG activity recorded from several intrinsic and extrinsic hand muscles failed to reveal active feedback regulation of contact force in this situation. Instead, in all experimental conditions, EMG data revealed a strategy of feed-forward stiffness modulation. (Winges et al., 2007).

Vision provides critical information for control of task kinematics. In reaching, we use vision to locate objects in the environment and to identify contact sites for the digits that will be stable and advantageous for various actions we want to perform with the grasped object (Lukos, Ansuini, & Santello, 2007).

Sarlegna et al., (2010) studied whether vision of the object contributes to the predictive control of grip force once the object is grasped. For this purpose, they delayed the visual feedback of object motion while participants manually tracked a sinusoidal target by oscillating a handheld object whose current position was displayed as a cursor on a screen along with the visual target. A delay was introduced between actual object displacement and cursor motion. This delay was linearly increased (from 0 to 300 ms) and decreased within 2-minute trials.

Participants had to track a visual target oscillating horizontally with a cursor representing the position of a handheld object. The participants were instructed to continuously move the handheld object in the fronto parallel plane to track the target with the cursor as accurately as possible.

Tracking performance was assessed by computing the root mean squared error (RMSE) and the time lag between target and cursor motions (using cross-correlations) to determine whether tracking errors resulted from the cursor preceding or following the target. To analyze movement kinematics, hand position (estimated from load force) was differentiated to obtain velocity and acceleration signals. The absolute values of peak velocity, mean velocity, and peak acceleration were calculated.

The grip force (GF)–load force (LF) coupling was assessed using cross-correlation between GF and LF, which provides a correlation coefficient (*R*) and the temporal relationship (lag) between the two signals was also calculated.

Delayed visual feedback altered performance in manual tracking. When the visual delay was 300 ms, the cursor lagged behind the target by 100 ms, meaning that participants partly compensated for the visual delay by having their hand motion preceding target motion by 200 ms. However, by the end of the trials when the visual delay decreased to 0, the cursor–target lag decreased and even became negative. Because the cursor was now preceding the target, RMSE increased again. Also, delayed visual feedback affected the temporal coupling between GF and LF such that the two signals were less synchronized. Indeed, in all delay trials, GF were shifted forward and thus preceded LF as a function of the visual delay. When the visual delay was maximal (300 ms)GF preceded LF by about 80 ms, whereas GF preceded LF by nearly 30 ms at the initiation of delay trials (as in PRE trials).In summary, although the physical properties of the handheld object remained strictly identical, the visual delay affected the predictive control of grip force, shifting forward its modulation (up to 50 ms). A phase lag between the two signals also shows that the visual delay increased the asynchrony between GF and LF. Importantly, although the physical properties of the object remained unchanged, delayed visual feedback altered the timing of grip force relative to load force by about 50 ms .When participants received visual feedback of the object load force on a computer monitor they also had tactile feedback of the object load force at the object–finger interface as well as proprioceptive feedback from muscular and joint receptors. When there was visual delay, the delayed visual feedback affected manual tracking performance. This study showed that delayed visual feedback affected grip force control when participants moved a handheld object. More specifically, the temporal synchrony between grip force and load force decreased as a function of the visual delay. Seeing a sinusoidal moving target in real time with a delay between target and cursor motion causes participants to have difficulty in predicting target trajectory and thus produced an action that is not very accurate and affected their performance. There was no significant correlation between participants' ability to compensate for the visual delay as reflected by the cursor–target lag and grip–load force synchrony. In other words, the participants who compensated the most efficiently for the visual delay were not necessarily those who exhibited the largest changes in grip force control. This study showed that the predictive control of grip force was influenced by delayed visual feedback. The authors of this study showed that vision still contributes to grip force control after the object has been grasped, even when somatosensory feedback was available. (Sarlegna et al., (2010)

Anticipatory parameter control uses vision or previous experiences during object manipulation. All participants used vision to identify which of the three object shapes were presented (corresponding to -30, 0, and 30° surface angles) and then retrieved information about the required finger forces from memory of previous lifts with these specific shapes (Jenmalm et al., 1997). Relying on visual shape cues, participants adequately anticipated the balance required between the horizontal grip force and vertical lifting force for grasp stability.

Feedback control

The nervous system monitors sensory signals and uses the information to act directly on the limb. Such moment-to-moment control is called feedback. Feedback is extremely important in minimizing movement errors and making timely correction to unexpected slips or disturbance.

Feedback sensory information represents mechanical events that take place at the skin-and-object interface. For example, the feedback control process would automatically modify motor commands and update the sensory motor memories in the brain to support predictive grip force control. In this manner, it prevents objects from slipping. Hence, the feedback control process supports the central nervous system using monitor-specific peripheral sensory events. It even helps in producing control signals required for making appropriate grip force adjustments during object manipulation in moment-to-moment control.

During the movement, sensory feedback from cutaneous mechanoreceptors and other sources is used to inform the central nervous system (CNS) about completion of various phases of tasks and to trigger subsequent phases. During the task in which an object is lifted from a support surface with precision grip and then replaced on table, fast adapting type 1 afferents fibres signal the initial contact and the final release of the digits (Kandel et al., 2000). Sensory feedback is important in providing relevant information about the object's properties and mechanical events. For example, such a mechanism is required near the skin-and-object interface to modify motor commands. During object manipulation, this helps to update if there are any inappropriate motor commands that result in slip or during generation of excess grip forces. (Kandel et al., 2000).

Johansson and Westling (1984) analyzed grip force adjustments during grasping, lifting, and holding an object with constant load. They demonstrated selective impairments of grip force regulation, such as less precise adjustment to the skin ± object friction and temporal delays in the triggering of subsequent force adjustment phases, when participants performed the lifting trials with anaesthetized grasping fingers. (Johansson and Westling., 1984)

Participants were asked to lift a small object with precision grip to about 2 cm above a table hold in this position for 10 s, and then replace and release. The surface structure was pseudo-randomly varied between sandpaper (No. 320), suede, and a finely textured silk. The experiments were repeated during local anesthesia of the index finger and thumb. The ratio between the grip force and the load force as a function of time was calculated. This ratio described the balance or coordination between the two forces. The moment that the index finger and thumb, respectively, first touched the object was assessed from the differentiated grip force records.

By comparing the trials with corresponding trials preceded by no change in surface structure, the course of adjustment to the new surface structure was studied. The influence of the new structure commenced about 0.1 s after the object was gripped between the index finger and the thumb. However, complete anesthesia of the index finger and thumb impaired the adaptation of the force coordination to the frictional condition; hence, the adjustment to friction was dependent on signals from cutaneous afferents innervating the skin area in contact with the object. During anesthesia, the transition between the preload and loading phases was distorted. The preload phase was prolonged and lasted up to 0.5 to 1.0 s compared to normal conditions. Grip force continuously increased and reached considerably higher values at the start of the loading phase (typically 5 times higher than normal). These findings suggested that afferent signals from the fingers provided information about the contact condition between the fingers and the object. These signals were necessary for the parallel force changes. Hence, mechanoreceptors provide the necessary feedback information during manipulation of grasped objects.(Johansson and Westling.,1984)

Johansson (1992) examined the control of grip force adjustments when an instrumented manipulandum held in a two-finger grip was subjected to various amplitudes of load forces that tend to pull the object away from the grip. Participants used the thumb and index finger to grasp (pulp to pulp) and restrain a manipulandum with two parallel grip surfaces attached to a force motor which produced distally directed (pulling) loads tangential to the finger tips.

The two grip surfaces of the manipulandum were connected via stiff parallel beams (10 cm long) to the rotational axis of a torque motor, thus making it an active object. Three force amplitudes were delivered in an unpredictable sequence; 1N, 2N, and 4N. The movement of the manipulandum, the load forces, and grip forces (normal to the grip surfaces) were recorded at each finger. Participants were asked to prevent the manipulandum from moving during the loading trials that exerted unpredictable loading forces. When handling this manipulandum the grip force responses to the changes in load were delayed. This task exerts unpredictable forces that cannot be adequately represented in a sensorimotor memory. Consequently, the manipulation may be more reliant with a moment-to-moment sensory control which is feedback control.

Hammond et al. (2010) evaluated changes in temporal and amplitude movement accuracy with tasks requiring fine motor manipulation with and without the use of the index finger (WIF). Motor performance was quantified during manipulation of a pen, cork, and wine glass using a computerized visual guided tracking task. Out of the three tasks, pushing or pulling the LEGOcar showed the largest temporal errors; in particular, pulling the car back exhibited the greatest error in temporal accuracy. This may be explained by the more difficult process of sensing and controlling the horizontal shear force of the pen acting tangential to the car surface in producing the backward motion. Participants were consistently more in phase reaching the maximum forward position (median: 129 ms), compared with the backward position in the normal condition (median: 186 ms; $p \leq 0.003$; $d = 0.53$). Hence, sensory feedback regarding the interaction of the pen and the car was needed of this task.

In a study by Sarlegna et al. (2010), task complexity was increased by making target motion less predictable. In unpredictable tasks, cursor–target lag increased when the complexity of the target motion increased (throughout the first 65 s). Conversely, when the complexity of target motion decreased, both RMSE and cursor–target lag decreased. The ANOVA on the cursor–target lag showed a significant effect of complexity ($p < 0.001$). Tracking targets that do not have predictable paths thus needs continuous corrections, and in this case, vision provides target coordinates and thus feedback is visual.

3. Movement Accuracy and Precision Level

Manipulation of everyday objects with a wide range of physical properties such as size, shape, weight, inertia, and location of mass center, often require a high degree of precision, small deviations in timing or endpoint positioning/orientation of the object, leads to complete disruption of performance.

Computerized visual tracking tasks have been used to quantify spatiotemporal accuracy of fine motor manipulation skills in participants. A predictable sinusoidal visual tracking task with configurable amplitude and frequency provides a method to control consistency and reproducibility of predictable movement task (Carey et al., 2002; Nowak et al., 2005; Yamanaka et al., 2005 and Hammond et al., 2010).

Hammond et al., (2010) used a customized software program by which a cursor (large bright-colored circle) could move onscreen either horizontally or vertically in a predictable sinusoidal manner. The study showed that this assessment tool was a reliable and valid method of objectively evaluating finger–hand function in the manipulation of many different objects with a range of task precision.

They evaluated the changes in temporal and amplitude movement accuracy in three precision tasks requiring fine motor manipulation, with and without the use of the index finger. A predictable sinusoidal visual tracking task with configurable amplitude and frequency was used to evaluate consistency and reproducibility of predictable movement tasks. Manipulations were done with either 2 or 3 fingers for each task, which included (a) two-digit rotation of a wine cork to represent manipulation of small object or knob; (b) three-digit manipulation of a pen used to push or pull a small four-wheeled platform forward and backward to emulate the use of an implement, such as writing or pushing food on a plate; and (c) three-digit manipulation of a plastic wine glass, holding onto the bottom of the stem and tilting the top of the glass forward and backward. In the without index finger (WIF) condition, two-finger manipulations occurred with the thumb and long finger, and all three-finger manipulations occurred with the thumb and the long and ring fingers. The participants performed these tracking tests using objects instrumented with a miniature miniBird™, 6 degrees of freedom motion sensor of 8 mm diameter (Ascension Technology, Burlington, VT). The position coordinates of the onscreen moving target cursor and the position and orientation coordinates of the miniBird™ motion sensor signal (actual object motion) were recorded.

A cross-correlation was performed to compare the actual object motion to that of the reference motion trajectory. The resulting r-value was used as an index of global performance in the manipulation of the three objects. When quantifying the temporal accuracy, the maximum and minimum points in the movement trajectories of the actual movements were compared to the reference cursor trajectory. Absolute temporal accuracy was analyzed by calculating the mean phase differences (milliseconds) between the peaks and the valleys of the reference and performance waveforms for the cycles in each trial. Amplitude consistency was determined by the coefficient of variation and measured by the magnitude of excursion from the minimum to the maximum position of the performance sinusoidal curve for each consecutive cycle. The three objects and tasks varied in degree of complexity and had different functional requirements due to their shape, mass, and load torque. There was no load torque in two-digit rotation of a wine cork, so this task had the lowest level of precision. Tilting the long-stemmed wine glass had large torque load. Pushing and pulling a four-wheeled platform LEGO car using a pen is a high-precision demanding task. No significant differences in cross-correlation coefficients were found between the two conditions during either the cork task or wine glass task. However, significant differences were found with the pen task; the performance index was greater (better performance) when using the normal grip as compared with the WIF condition ($p \leq 0.03$).

In the pen task, there was a significant difference in temporal accuracy when comparing the forward and backward end points. This may be explained by the more difficult process of sensing and controlling the horizontal shear force of the pen acting tangential to the car surface in producing the backward motion. Tilting the wine glass forward and backward was the more difficult task, as indicated by the substantial increase in amplitude variation from cycle to cycle. Because participants were instructed to follow the onscreen cursor with respect to speed and height, the inability to control the amplitude can be attributed to difficulty in controlling torque in an unfamiliar posture.

During the WIF condition, the most significant decrement in performance was observed for the pen task. This was true for both the global performance measure and temporal errors. The pen task required timely sensory feedback to control forces through the pen to push the car forward (vertical forces acting normal to surface) and pulling the car backward (horizontal shear forces tangential to surface).

In general, decline in performance during the WIF condition is, in part, likely due to familiarity with the tasks. Holding a pen, utensil, or other implement are tasks completed many times a day with years of experience.

So, manipulation of objects from simple to complex demands a high degree of movement accuracy. When the precision level of a task is low, there was no change in movement accuracy; however, when the task demands more precision, like pushing and pulling a four-wheeled platform LEGO car, there was difference in temporal accuracy. Also, as the task difficulty increases, amplitude variability was also seen. So, as precision demand increases, accuracy of object motion will be affected.

4. Summary of Literature Review

With a few exceptions (Hammond et al., 2009 and Hammond et al.,2010), the above studies have focused on control of grasp stability during lifting and transport tasks where movements were produced by wrist or elbow and fingers used to "clamp" objects and the physical properties of objects are stable and predictable. However, manipulation of objects with fluids involves unpredictable torque levels created by moving centre of mass and its position. During manipulation of objects with fluids, the location and orientation of contact forces change as the fluid moves. Due to variability in the centre of mass position, the grasping force increases accordingly. Another area that needs scientific attention is quantification of task precision during manipulation of objects with variable centre of mass locations. The present study deals with changes in the grip force pattern and movement accuracy when there is a variation in external torque levels.

Objects that contain fluid pose a unique feature because, if the object is tilted, then the fluid and thus the centre of mass of the object move. Hence, when we manipulate an object like a coffee mug, the fluid movement is unpredictable. Therefore, timely tactile sensory feedback and rapid corrective movements are required to prevent slips and unwanted spills (Gao, 2005; Smith, 2005; Soechthing & Flanders, 2007; Zatsiorsky & Latish, 2004). These studies have done research on rigid objects that had predictable centre of mass conditions, i.e., the COM fixed within the contact plane or below the contact plane, where feed-forward control strategy was used to stabilize the object during movement. However, they have not looked at the unpredictability created by moving the COM and its position. Therefore, it is important to study the effect of unpredictable centre of mass conditions and look at the different strategies involved in object manipulation.

The majority of studies to date have evaluated horizontal and vertical object transport tasks, where the fingers and hand are used to grasp and hold objects, while motion is produced by elbow and/or shoulder muscles (Winges et al., (2007); Wing and Lederman (1998); Jenmalm and Johansson (1997); Flanagan and Wing (1993).In these studies, a hand-stiffening strategy was observed, which particularly involves isometric and co-contraction of intrinsic and extrinsic finger muscles.

Many of the previous studies have examined motor performance while manipulating solid objects with predictable centre of mass conditions (Winges et al., (2007); Wing and Lederman (1998) .Most of our daily activities require precise manipulation of objects, which needs coordination of finger forces to counteract external torques in dynamic tasks like pouring liquids from one container to another, taking a spoonful of soup to the mouth, holding a wine glass, or pouring laundry detergent. Torque levels might vary based on the task that we perform. Therefore, it is important to look at the changes in the grip force pattern when there is variation in external torque levels during actual object manipulation. There is also a need to examine and understand all the factors that govern spatial and temporal accuracy and contact force regulation during object manipulation produced by the thumb and fingers. Previous studies have not used tasks where precision was a primary requirement. Hence, there is a need to quantify spatiotemporal accuracy of tasks that require precision.

5. PURPOSE, OBJECTIVES, AND HYPOTHESIS

1. Purpose

The purpose of the present study was to extend the current methodologies and protocols to include an evaluation of how movement performance of the thumb and fingers were modified during manipulation of objects with and without fluids. Further to quantify movement performance and accuracy during manipulation of objects, in two different modes of manipulation, ie, pendulum and inverted pendulum where the thumb and fingers are producing the motion with the wrist and elbow stabilized.

2. Objectives

A. To evaluate the effects of a moving mass centre, i.e., fluid-filled versus solid objects, on movement performance and pattern of digit contact forces during predictable and episodic task conditions.

Specifically task conditions included the following:

(a) Cyclic (predictable) open-loop hand-tracking task. This task was guided by a moving cursor on a computer monitor. In this task, the participant was asked to tilt the cup in concert with motion of the target cursor condition moving up and down at a fixed frequency and amplitude.

(b) Cyclic (predictable) closed-loop hand-tracking task. In this task, two cursors of different colors appeared on the monitor. One is the target cursor as in open-loop condition and motion of the second cursor was slaved to rotation of the cup using a custom motion sensor. The task goal was to overlap the two cursors during motion from top to bottom edge of the monitor. Thus the participant required continuous visual feedback in order to determine the amount of overlap (error) between the target cursor and the motion of the cup. Hence it required greater level of precision than the open-loop task.

(c) Episodic short duration point-to-point movements to visual targets.

A custom video game was used for this purpose. The goal of the test game was to move a paddle (game sprite) to catch moving objects (targets) moving horizontally left to right. The target objects appear every 2 seconds at random locations on the monitor from the left side of the screen.

Two coffee cups of 6.5 inches height (that is filled with water) were used for this purpose. (See Figure 1). One cup (fluid) is filled with 325 ml of water to occupy ½ the space; the mass of the cup would move as it is tilted, and this produced an unpredictable moving COM location. A second cup (solid) was filled with the same quantity of water (325 ml), and a Styrofoam insert was placed on top to fill in the remaining space. This produced the same mass and initial COM location that would remain fixed during the object tilt.

B. To evaluate the effects and interactions of type of movement strategy, pendulum and inverted pendulum modes on movement performance and finger-force profiles during manipulation of the coffee cups described in objective 1 in both predictable and episodic task conditions.

Many objects used in our daily life are manipulated, by holding them either above the COM (such as drinking from a bottle) or by holding them below the COM (such as drinking from a cup glass or bottle). These can be modeled as a pendulum holding the object above the axis of movement (P-mode), or as an inverted pendulum holding the object below the axis of movement.

The modes of manipulation involved were as follows

(a) Inverted pendulum mode (IP-mode) where digit contact was at a marked location near the bottom of the cup, below the centre of mass (COM).

(b) Pendulum mode (P-mode) where digit contact was at a marked location near the top of the cup, above the COM.

3. Hypotheses

A. There will be no difference in movement performance when manipulating either solid or liquid-filled cups (object properties) for the predictable, cyclic tracking task. However, changes in movement performance will be seen during the episodic tasks conditions. It is expected that during a repetitive cyclic task, there is an opportunity to learn the mechanical effects of fluid motion and thus, to predict in advance the means to correct the fluid motion during tilts.

B. There will be no difference in movement performance when manipulating fluid-filled cups in pendulum or inverted pendulum mode of manipulation in both the tasks. Adults can have extensive exposure to the dynamics of objects with varied COM locations, and past experience could account for the lack of any effect of mode of manipulation on the temporal organization and variation in movement amplitude.

C. The magnitude of total digit forces would be increased in the fluid condition compared to the solid condition. While manipulating a solid cup, people can become familiar with object properties, thus they can tailor fingertip forces for the properties of the object to be manipulated prior to performing the task through their memory pertaining to the object properties. However during manipulation of a fluid-filled object about a vertical axis, then the gravitational and inertial loads will change in an unpredictable way as the object moves. Therefore, timely sensory feedback controls have a crucial role to play in taking rapid corrective action to accommodate these mechanical events and to minimize movement errors or slips. This can result in application of greater contact forces.

MATERIALS AND METHODOLOGY

Data Recording and Measuring Instruments

MiniBird motion tracker™

The MiniBird™ pulsed DC magnetic tracking system (Model 800 DC) with miniature motion sensor (Ascension technology, Burlington, VT) was used to instrument the cups (See figure 2). It is reliable and allows precise measurement of the 3-D spatial position and orientation of any object sampled at 35 Hz. This study used a sensor head of size 8 mm x 8 mm x 18 mm and 0.8 g in weight with a sensor resolution of position: 0.5 mm, orientation: 0.1° @ 30.5 cm .The sensor is capable of recording linear and angular position on 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. Each cup was instrumented with the minibird™ sensor at a marked location to ensure correct placement with each participant and over time. The position of the cup relative to the magnet was kept constant during data collection. A permanent mark was placed on the cups that need to be manipulated during the task, to ensure consistent placement in each trial. The participants were asked to sit comfortably in the same position in front of the computer monitor, and the cups were positioned in such a way to ensure that the direction of motion was consistent across all participants and trials.

Finger-force sensors

Individual miniature force sensors (Force Sensitive Applications [FSA] Verg Inc., Winnipeg, Man.)(See Figure 3) were used to measure the contact forces between the finger digital pads and the object. These were taped to the digital pads of the thumb, index and middle finger using a two-sided tape. These pressure sensors were calibrated to record from zero to 10 psi force. The flexible piezo resistive sensors (1 cm square) are ultra thin, and their interference with the object manipulation is minimal, once the surface texture (coefficient of friction) is modestly adjusted. Saran wrap was used around the object to adjust the coefficient of friction. Placing sensors on the fingers (thumb, index, and middle) instead of on the object being manipulated allowed greater versatility and spatial resolution.

Experimental Set-Up and Test Protocol

Participants

Twenty healthy right-handed participants ages 20 to 35 were recruited for this study from students and staff at the University of Manitoba and Health Sciences Centre via advertisement. Participants were excluded if they had a history of upper-limb pathology (with residual deficits), recent injuries to the right arm, cognitive impairments, or a history of neurological impairment (affecting balance, vision, or coordination). Participants were fully informed about the procedure, and 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 previous studies, it was estimated that 20 participants would provide reliable results, allowing credible conclusions to be made. This study has been approved by the University of Manitoba Health Research Ethics Board (HERB), Bannatyne campus, University of Manitoba (H 2009:087).

Test Protocol

The participants were asked to complete each assessment protocol using 2 identical coffee cups. These cups were manipulated using a prismatic grip – a grip by the tips of the digits in which the thumb and the index finger oppose each other (Zatsiorsky & Latash., 2004).

Participants were asked to wash their hands 5 minutes before the trial. They were made to sit comfortably in front of a computer monitor to perform the object manipulation tasks. Their arm was positioned approximately in 20 degrees shoulder flexion and neutral rotation, elbow in flexion, and the forearm in pronation and resting on a four-inch block of Styrofoam. A strap was used to eliminate any vertical motion. The wrist was flexed approximately 40 degrees, which also helped to prevent forearm or shoulder motion and contributed to the forward-backward motion of the cups. (Figure 4). The participants were instructed to rotate the cups (towards and away from the body) in pace with the moving computer cursor. The duration of each trial was 20 seconds, producing around 12 cycles for analysis. Participants were allowed to have one practice trial to become familiar with the tasks. The orders of the cups were manipulated, and the two modes of manipulation i.e., P mode and IP mode (See figure5) were randomized in order to minimize a potential training or order effect.

In addition to the cursor task participants were also instructed in playing a computer game. The test game was instrumented with an assessment module that generates a logged game file to record (100 Hz) the following signals associated with actions performed by a participant with respect to game play events: (a) coordinates and timing of each game event (specific task goals), and (b) coordinates of the computer mouse (game sprite) slaved to physical motion of player, in this case, cup rotation. The following three experimental tasks were used in the study:

1. **Cyclic (predictable) open-loop tracking task (Figure 6)**

This task was guided by a moving cursor on a computer monitor. In this task, the participant was asked to rotate the cup in concert with motion of the target cursor condition moving up and down at a fixed frequency and amplitude. Custom software was created to move an on-screen cursor (large bright colored circle) in a predictable sinusoidal manner either horizontally (left to right on the display) or vertically (top to bottom on the display).

2. **Cyclic (predictable) closed-loop hand-tracking task (Figure7)**

In this task, two cursors of different colors appeared on the monitor. One is the target cursor as in the open-loop condition which was moving up and down. Motion of the second cursor is slaved to rotation of the cup using a custom motion software program. The task goal was to overlap the two cursors during motion from the top to bottom edge of the monitor. Thus the participant required continuous visual feedback in order to determine the amount of overlap (error) between the target cursor and the motion of the cup. Hence it required greater level of precision than the open-loop task.

3. **Computerized Episodic task: Random movements (Figure 8)**

These are episodic short duration precision movements of varying direction and amplitude presented randomly. A custom video game was used for this purpose. The goal of the test game is to move a paddle (game sprite) to catch falling objects (targets) moving horizontally left to right. The target objects appear every 2 seconds at random locations on the monitor from left to right.

The task complexity level which was used is as follows: Simple, involving a single target object to catch, which was a bright-colored circle, moving horizontally from left side of the monitor to right. During game play, if the participant catches the target circle objects, then a point was scored. If he/she misses, then the paddle blows up for 4 seconds, i.e., the participant receives a penalty. Each game lasts for 120 seconds.

Figure 9 (left panel) displays the raw motion coordinates of the computer game paddle sprite contained in one logged game data file. In this case, the game paddle was slaved to the rotation of the cups, i.e., the minibird™ sensor (See Figure 2) was attached to the cup. The cups were being positioned in such a way to ensure that the direction of motion was consistent across all participants and trials.

Data Recording and Analysis

The position coordinates of the onscreen moving target cursor and the 3-D position and orientation coordinates of the MiniBird motion sensor (actual object motion) were synchronously logged at 35 Hz and saved to a file. The coordinate data of each trial was then processed using custom analysis routines written in MATLAB version 7.1 (Math Works, Natick, MA) and then exported for offline analysis. This software program could perform signal and accuracy analysis. Of the 12 movement cycles recorded, the first 2 cycles were excluded to ensure participants reached a consistent movement pattern, synchronously with the moving computer cursor. The middle 10 cycles was selected for all participants and trials. The motion data of each trial was filtered with a 4 Hz low-pass filter to reduce noise in the signals. Signal analysis included subsets of whole-signal peak-to-peak and RMS. Accuracy analysis was used to compare reference wave form with performance wave form and used 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 force signals was calculated for different tasks to analyze change in grip forces as a function of object property. Cross-correlation was computed between the target (reference) cursor motion and actual cup motion in the primary direction. The maximum cross-correlation coefficient (MCC) was used as an index of movement performance in the manipulation of the two objects. MCC of the reference frame with the actual movement signal was used to understand the similarity between the two signals. MCC between target cursor and actual movement trajectory was quantified.

A. Dependant Variables from Predictable Mode of Assessment (Open-loop and Closed-loop Tasks)

The following outcome measures were computed from the logged coordinate motion data obtained during the cyclic open- and closed-loop hand-tracking tasks:

1. Maximum cross-correlation coefficient (MCC) obtained from cross-correlation analysis of reference target trajectory and actual object motion trajectory.
2. Temporal accuracy of each movement cycle maxima and minima (motion turning points).
3. Amplitude consistency determined by the coefficient of variation (CV) and measured by the magnitude of excursion from the minimum to the maximum positions of the performance sinusoidal curve for each of the consecutive cycles, i.e., each direction of movement.
4. RMS of the digit force signals.

1. Cross-correlation analysis

Cross-correlation analysis was used to obtain maximum cross-correlation coefficient (MCC). MCC obtained from the cross-correlation function that examined correlation of 2 waveforms. A cross-correlation is a measure of similarity of two signals, and the MCC was used to index movement quality of signal trajectory relative to the reference target trajectory. MCC was obtained from cross-correlation analysis of reference target trajectory and actual object motion trajectory.

A cross-correlation analysis was performed in both open-loop and closed-loop modes between target cursor trajectory and actual movement trajectory to find out the effect of fluid motion under each torque condition, i.e., P-mode and IP-mode (See Figure 5).

The magnitude of the contact forces for each digit was analyzed by computing the root mean squared (RMS) of the force signal amplitude. The minibird™ data was sampled at 35 Hz, and sampling frequency of finger-force data was 125 Hz. A cross-correlation analysis was done between movement trajectories and force signals in both open-loop and closed-loop modes during each object manipulation and under each torque condition in order to study the effects of each independent variable on the grip force used.

The performance wave form was correlated to the reference wave form for each trial and the resultant r-value was used as an index of movement quality.

The peak value of the cross-correlation has been used to indicate the relationship between the target and tracking signals when participants followed the target pattern in a visuomotor tracking task by moving their finger. This function was used to examine the effect of motor training on finger tremor in the context of skilled motor performance (Dartnall et al., 2009).

In a recent study by Kapadia et al., (2008), peak cross-correlation (PCC) was used as an outcome measure to quantify the motor performance. Another study by Andersen Hammond, Szturm, and Shay (2007) used PCC as an index of motor performance and endpoint movement accuracy of visual-guided cyclic tracking tasks involving thumb-finger manipulation of three common objects.

2. Temporal accuracy

Temporal error was quantified to evaluate accuracy in reaching maxima and minima of the sinusoid with respect to time (ms) from the performance peak to reference peak and performance valley to reference valley for the middle selected 10 cycles. That is, the time between maxima and minima points of each movement cycle was subtracted from the respective target cursor maxima and minima times. The overall temporal difference, either lag or lead, was computed. Temporal error was computed and compared to evaluate the changes in timing between IP-mode and P-mode of manipulation, with and without moving centre of mass condition. Average absolute temporal accuracy (ms) of the turning points (maxima and minima) of the10 cycles was determined.

3. Amplitude consistency

To evaluate the consistency in the amount of object motion in directions, the average amplitude excursion and variance of each half cycle of Minibird™ (defined by turning points or maxima and minima positions) was computed. The first two cycles were excluded, and the middle 10 cycles selected for temporal analysis was selected for amplitude analysis.

Amplitude consistency of the 10 cycles was determined by the coefficient of variation (CV) and measured by the magnitude of excursion from the minimum cup position to the maximum cup position of each consecutive cycle. (Figure10)

Amplitude consistency of the middle 10 cycles determined by the coefficient of variation (CV) is computed by "standard deviation divided by mean expressed as a percentage of 100."

The coefficient of variation represents the ratio of the standard deviation to the mean, and it is a useful statistic for comparing the degree of variation from one data series to another, even if the means are drastically different from each other. Its formula is,

$$C.V = \frac{\sigma}{\overline{X}} \times 100$$

In summary, the temporal and amplitude error calculated using miniBird™ data provided information regarding movement accuracy over a range of independent variables.

4. Root mean square (RMS)

The magnitude of the contact forces for each digit was analyzed by computing the root mean square (RMS) of the force signal amplitude. The RMS values calculated from the force signals provided information regarding grip forces used over a range of independent variables.

B. Dependant Variables Random Mode of Assessment (Analysis of Motor Performance from Game) (Figure11)

We have developed a universal hand-function assessment system. It includes an automated tracking and assessment system (ATA) that makes it possible to instrument any object with a miniature motion sensor and transform it into a standard computer mouse Otto, C. (2007). Thus, a person can manipulate objects while playing a "random" video game analysis. Procedures have been developed to quantify movement accuracy, movement quality and also movement efficiency from the data collected from the video game protocols. This assessment subsystem generates a logged game file and records the following signals associated with actions performed by participants with respect to game play events:

(a) Coordinates and timing of each game event (specific task goal, i.e., hitting a moving target with paddle on computer screen).

(b) Coordinates of the computer mouse (game sprite) slaved to exercise movements (instrumented objects coffee cups).

(c) Coordinates of the measured motion signals of the instrumented objects; 3-D linear trajectories and 3-D angular trajectories obtained from the miniature six-degrees-of-freedom motion sensor.

The participant performance during game play can be quantified from the following variables:

1. The game score.

It is calculated as success rate as percentage of target object caught. Each time a player moves the game paddle by tilting the cup so that it collides with a moving target, the game score is incremented by 1.The total number of paddle misses during a gaming session is recorded with the counter in the upper left-hand corner of the game panel display. The game records a player hits and misses.

2. The average motor initiation time.

It is calculated as the time from the appearance of the target to start of the paddle movement; this output variable is gathered by looking at the velocity curve for each of the user movement trajectories. The maximum point of the velocity curve was considered the beginning of the movement. The sample that coincides with the maximum velocity was considered the starting sample for the movement for a given event. The sample value was then converted to a time in milliseconds based on the sampling frequency. It is calculated by subtracting the maximum velocity sample from the event start time. These times are averaged together to give a more accurate picture of the overall response time of the player.

3. The average movement execution time

It is calculated as 90% of the time between movement initiation and final paddle position. We consider only 90% of the time because there is a latency period of 10% between target appeared and person hitting the target .This event is triggered as soon as a target enters the screen. From that point, the user movement is timed, and then they either reach the target and destroy it or miss. This variable quantifies how long it takes the user to reach 90% of the distance to the target from the start of an event. For those events where they successfully hit a target, the rise time is included for 90% of the movement trajectory to give us an idea how long it took the user to get close to the target. It gives an idea of the players' game play strategy and to see whether they were making controlled slow movements or really rapid sweeping actions in the hopes of contacting the target.

C. Statistical Analysis

A repeated measure of analysis of variance (ANOVA) was used to evaluate the influence of object properties (solid vs. fluid), mode of manipulation (pendulum and inverted pendulum modes of manipulation), and degree of precision using a cyclic, predictable task and a series of precise episodic tasks (varying in direction and amplitude) on amplitude consistency, temporal accuracy, and grip forces (normal and tangential forces). A P value of 0.05 is considered statistically significant. Temporal accuracy and amplitude consistency are used to identify possible relationships between target trajectory and movement trajectory and between object movement trajectory and force profiles.

A repeated measure analysis of variance (ANOVA) was used to evaluate the influence of object properties (solid vs. liquid) and torque levels (pendulum and inverted pendulum) on the score, average motor initiation time and average movement execution time.

A P-value of 0.05 was considered statistically significant. Score, average motor initiation time and average movement execution time, give an idea of the user game play strategy and to see whether they were making controlled slow movements or really rapid sweeping actions in the hopes of contacting the target.

RESULTS

The experimental tasks consisted of having the participants performing two visually guided tracking tasks and episodic short duration precision movements of varying direction and amplitude presented randomly. In the open-loop 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. The closed-loop task required overlapping of two cursors during motion from top to bottom edge of the monitor. The third task was to move a paddle (game sprite) to catch falling objects (targets) moving horizontally left to right.

The tasks in this study were recorded with a Logitech™ web camera model Pro9000. The digit postures and segment motions were determined from visual observation of video playback. During the IP-mode of digit manipulation, the thumb is held in palmar-abduction with slight metacarpo-phalengeal joint (MCP) and interphalengeal joint (IP) flexion. During forward rotation of top of the cup, a small amount of thumb rotation (in the direction of opposition) was also required.

During IP-mode, the middle finger slightly flexes and extends at the (MCP, PIP, and DIP) joint while the index finger rotates (clockwise-forward and counter-clockwise-backward) around the longitudinal axis to accommodate and maintain contact of digit tip with object. In case of P-mode, the thumb acts to push and rotate the bottom of the object backwards, and a larger amount of thumb rotation and opposition is required. MCP joint flexion and extension of fingers is also required to move the bottom of the cup backwards and to bring the cup in to neutral position assisted by restoring gravitational force.

Forward tilting of coffee cup required that participants hold the bottom of the cup in IP mode and Top of the cup in P mode between the thumb, long, and ring fingers and tilt the glass away from the body (maximum position) and then toward the body (minimum position).

Results of Predictable Movement Tasks

Performances during manipulation of fluid-filled cups in both P- and IP-modes were compared in both open-loop and closed-loop modes. Figure 12 present's typical plots of reference target cursor and cup movement trajectories for IP-mode (top panel) and P-mode (bottom panel) of one representative subject in open-loop mode. Figure 13 present's typical plots of reference target cursor and cup movement trajectories for IP-mode (top panel) and P-mode (bottom panel) of one representative subject in closed-loop mode.

As evident in Figures 12 and 13, the actual object trajectories during both P- and IP-mode were different in closed- as compared to open-loop mode for both solid and liquid. In open-loop mode, the movement profiles exhibited regular cyclic pattern in both P- and IP-mode while manipulating solid and liquid cups. For the most part, actual trajectories exhibited consistent, regular sinusoidal patterns similar to the reference trajectory. Maxima and minima at the turning points were seen for each half cycle, and the phase (timing of maxima and minima, vertical lines) were similar.

Figure 14 shows the raw data figure of movement trajectory and finger-force profiles in closed-loop tasks. Distinct movement-related cycles of plateau and "off" period were clearly evident in all digits-force profiles in both modes of manipulation. (See Figure 14)

In the inverted pendulum mode, at the maximum forward position of the cup, the thumb forces peaked opposite to index finger forces, i.e., in the inverted pendulum mode, during the forward rotation of the cup, the thumb-force profiles increased, indicating that most of the load was transferred onto the thumb compared to the index finger. In the pendulum mode, at the forward position of the object, i.e., when the bottom of cup was tilted, both the thumb force and index finger forces peaked after the object maximum. (See panel left and right, Figure 14).

Results of the repeated measures ANOVA showed that there was no Effects of Fluid Motion (Fluid vs. Solid) and Mode of Manipulation (IP vs. P) on the Dependent Variables in Predictable (Open-loop) Mode of Assessment.

Table 1 Summarizes results of the repeated measures ANOVA for closed loop task. It illustrates that although task performance varied between participants, no significant differences in maximum cross-correlation (MCC) were found between the two conditions during either the solid vs. fluid or P vs. IP.

In the closed-loop task, there was a significant difference in temporal accuracy when comparing the forward and backward end points. For closed-loop mode, the time of max and minima or turning points for both solid and liquid cup was delayed in both IP- and P-mode in the closed-loop task. Both solid and liquid cups peaked after the reference peaked.

Significant differences were found with the mode of manipulation; the performance index was greater (better performance) when using the cup in P-mode as compared with the IP-mode (solid, $P = 0.005$); liquid, $P = 0.025$). A significant effect was seen with mode of manipulation on amplitude consistency (COV) in closed-loop mode with ($P < 0.001$).

Figure15 shows effect of mode of manipulation on MCC.There was no statistically significant effect of mode of manipulation on MCC in both closed and open-loop mode.

Figure 16 presents group means (SEMs) of amplitude consistency, coefficient of variation (COV) for each movement direction. There was no significant effect of fluid motion (solid vs. fluid) on amplitude (COV) in both open- and closed-loop mode. There was also no statistically significant effect of mode of manipulation on amplitude (COV) in open-loop mode. However, significant differences were found with the closed-loop task ($P < 0.001$). In closed-loop, mode of manipulation (IP versus P) had a significant effect on amplitude consistency max to min ($P < 0.001$, $F = 13.517$). Mode of manipulation (IP versus P) also had a significant effect on amplitude consistency min to max ($P < 0.001$, $F = 13.089$).

Figure 17 presents group means (SEMs) of temporal accuracy. There was no significant effect of fluid motion (solid vs. fluid) or mode of manipulation (IP versus P) in open-loop mode. However, in closed-loop, mode of manipulation (IP versus P) had a significant effect on temporal error maximum ($P<0.050$, $F=6.167$). Mode of manipulation (IP versus P) also had a significant effect on temporal error minimum ($P<0.050$, $F=5.346$) in closed-loop mode.

The quality of movement was better in pendulum mode than inverted pendulum movement.

Figure 18 presents group means (SEM) for RMS values of finger forces. In both open-loop and closed-loop mode, there was no significant effect of either fluid motion (solid vs. fluid) or mode of manipulation (IP versus P) on RMS of the finger contact forces.

Results of Episodic Movement Task

Table 2 Summarizes results of the repeated measures ANOVA for episodic task. It illustrates the effects of Solid vs. Fluid and Mode of Manipulation IP vs. P on the Dependant Variables in Episodic Mode of Assessment. This table Summarizes, no significant differences in dependant variables were found between the two conditions during either the solid vs. fluid or P vs. IP.

As presented in Tables 1 and 2, statistical analyses revealed no significant effect of fluid motion (solid vs. fluid) or mode of manipulation (IP vs. P) on dependant variables in both predictable and episodic tasks.

Figure 19 presents group means (SEM) of score from episodic movement task data. There was no significant effect of fluid motion (solid vs. fluid) or mode of manipulation (IP vs. P) on score.

Figure 20 presents group means (SEM) on movement execution time. 90% of the time between movement initiation and final paddle position, this variable gives an idea of the participant's game play strategy and to see whether they make controlled slow movements or really rapid sweeping actions in the hopes of contacting the target. This variable measures how long it takes for the participants to reach 90% of the distance to the target from the starting.

There was no statistically significant effect of fluid vs. solid or mode of manipulation, IP vs. P on movement execution time.

Figure 21 presents group means (SEM) on motor initiation time, the left panel for P-mode and right panel for IP-mode. This variable is gathered by looking at the time from the appearance of the target to start of the paddle movement: The response times are averaged to give a more accurate picture of the overall response time of the participants. The maximum point of the velocity curve was considered the beginning of the movement. The sample that coincides with the maximum velocity was considered the starting sample for the movement for a given event. There was no statistically significant effect on either effect of fluid motion fluid vs. solid or mode of manipulation, IP vs. P on movement time.

Figure 22 presents group means (SEM) for RMS values of finger forces in episodic movement tasks (Picture 8). There was a statistically significant effect of fluid motion (solid vs. fluid) on RMS of thumb ($P < 0.05$).Within solid and liquid, the mean value(RMS) for solid was 0.52 and liquid(RMS) was 0.36; hence, the solid had a more significant effect on RMS of thumb contact forces.

There was also a statistically significant effect of fluid motion (solid vs. fluid) on RMS of index finger contact forces ($p < 0.01$).Within solid and liquid, the mean value for solid was 0.39, and liquid was 0.16; hence, the solid had more significant effect on RMS of index finger. There was no statistically significant effect of mode of manipulation (IP vs. P) on RMS of thumb and index finger.

DISCUSSION

Most of the previous studies have focused on control of grasp stability during lifting and transport tasks where movements were produced by wrist or elbow and fingers used to "clamp" objects and the physical properties of objects are stable and predictable. However, manipulation of objects with fluids involves unpredictable torque levels created by moving centre of mass and its position. During manipulation of objects with fluids, the location and orientation of contact forces change as the fluid moves. The purpose of the present study was to extend the current methodologies and protocols to include an evaluation of whether movement performance and accuracy are modified during manipulation of objects with a stationary versus a moving COM (i.e., fluids). In these tasks, the thumb and fingers are producing the motion with the wrist and elbow stabilized. For this purpose, participants tilted forward and backwards a coffee cup that was half filled with 325 ml of water and another cup with the same amount of fluid and a Styrofoam filler to prevent fluid motion. These movements were performed in two modes of finger manipulation tasks: a) IP where the COM was above the contact points; and b) P where the COM was below the contact points in three different predictable and episodic task types.

The main findings of both types of analysis will be summarized before discussing their broader implications. The main findings were that, in predictable (open and closed loop) and episodic movement tasks, movement quality and movement accuracy were not influenced by a moving COM. The location of COM relative to digit contact point (P-mode versus IP-mode) did not influence movement quality in open loop mode. However, the location of COM relative to digit contact point did influence movement quality in closed loop mode as evidenced by maximum and minimum temporal and amplitude errors during IP-mode compared to P-mode. Thus the performance was superior when using the cup in P-mode as compared with the IP-mode.

Lastly, in both open and closed loop mode, the average force levels exerted by individual digits during the tasks were not significantly influenced either by moving COM (solid vs. fluid) or mode of manipulation (IP vs. P). However, in episodic movement tasks the average force levels exerted by individual digits during the tasks was significantly influenced by moving COM (solid vs. fluid). Overall finger forces required during manipulation were highest for solid cup, which had no moving mass centre, and lowest for liquid cup with moving COM. In episodic tasks, increased average force levels during the solid condition as compared to the moving fluid condition would relate more to exertion than to movement accuracy.

1. Effect of moving mass centre (COM)

A. Movement performance and Accuracy

A number of studies have observed that object manipulations during point-to-point translation or rotation where the thumb and fingers maintain a rigid posture are achieved using a hand-stiffening strategy with co-contraction of extrinsic and intrinsic hand muscles (Wing & Lederman, 1998; Winges et al., 2007, 2008). In these cases, the object is being moved by virtue of motion occurring at the wrist and/or elbow. In contrast to a stiffening thumb-finger strategy, the present study involves movement of fingers.

a. Predictive open and closed loop tasks

In both open loop and closed loop tracking tasks, there was no difference discerned in movement quality or temporal and amplitude accuracy at the turning points.

One reason why there was no effect of moving COM on performance measures was that during cyclic tasks it is possible that within a few cycles there is an opportunity to learn the mechanical effects of fluid motion and thus, to predict the means to account for the fluid motion during the predictable tasks. Previous studies have shown that during cyclic manipulation of irregular-shaped objects paced by a moving visual target, participants can quickly adapt within a few movement cycles and learn to predict complex gravity and motion dependant forces to significantly reduce spatial and temporal movement errors (Roerdink, Ophoff, Lieke, Peper, & Beek, 2008; Roerdink, Peper, & Beek, 2005; Russell & Sternad, 2001; Salmi, Hollender, Frazier, & Gordon, 2000).

Another reason for no change in movement performance with moving COM observed in predictable cyclic tilting tasks was most likely because these tasks are common well learned tasks that are practiced many times daily. Holding a coffee cup or drinking water from a glass or cup are tasks completed many times a day with years of experience. In a study by Schmitz et al. (2004), the authors suggested that sensorimotor memory representation acquired during previous manipulatory experience can store critical object properties. When the object was made unpredictable in a lifting task by changing it's weight irregularly between 230 and 830 gm, the authors didn't reveal any slips when they could not predict the changes in weight. It was concluded that knowledge of the object was sufficient to enable the individual to select and tune the appropriate control strategy. Consistent with the present results, Lukos et al. (2007) have shown that prior knowledge of object properties plays an important role in the selection of contact points. Participants were asked to reach, grasp, lift, and replace a T-shaped object consisting of a 78 mm diameter cylinder attached to a horizontal base with their right hand whose COM was changed to the left, center, or right of the object. For the predictable condition, participants were informed that object COM location would be the same for the entire block of trials. Participant's performance was quantified by measuring peak object roll i.e.; the angle about the vertical axis (roll) was measured. Because changing object COM introduced an external torque, the task requirement was to minimize object roll during lift. Peak object roll is an indirect measure of anticipatory force control, with smaller rolls being evidence of more accurate digit force scaling to the expected external torque after onset of object lift (Salimi et al., 2000). Participants were able to minimize object roll during lift to a significantly greater extent when object COM location could be predicted on a trial-to-trial basis. This implies that subjects were able to anticipate the digit forces necessary to counter the external torque caused by moment arm. This depended on the acquisition of implicit prior knowledge about object properties associated with repeated manipulations of the same object.

b. Episodic task

Previous studies quantified movement accuracy in predictable tasks. However, many everyday activities demand stability under unpredictable conditions. It was important to quantify how movement accuracy changes in short duration episodic tasks where direction and movement amplitude are not predictable. In the case of episodic tasks, our hypothesis was rejected because there was no change in movement performance.

Again reason to support this evidence is that the episodic task used in this study was not a novel task. The task involved manipulating a typical sized cup of moderate mass (350 g), and the speed and amplitude of the movements were typical of object rotations used many times in daily activities. Thus there were minimal constraints of mass or movement speed. Unlike in predictable tasks, in episodic tasks participants were making short amplitude movements by tilting objects to interact with the target object.

Previous knowledge of the object enables the individual to select and tune the appropriate control strategy. Chan (1995) has shown that previous experience with similar objects contributes to performance. This experience is gained through sensory feedback, including limb proprioception, and visual observation of the object's motion.

B. Magnitude of contact forces

Our study did not reveal any effect on RMS of contact forces during cyclic predictable tasks. However, episodic movement tasks manipulating a solid cup, i.e., no moving COM, had shown more significant effect on RMS of thumb and index contact forces, hence our third hypothesis was rejected as total digit forces increased in the solid condition compared to fluid condition.

One reason for no change in finger contact forces while manipulating a solid cup is perhaps due to familiarity with the objects. When people are familiar with object properties, they can tailor fingertip forces for the properties of the object to be manipulated prior to performing the task through their memory pertaining to the object properties (Johansson & Cole, 1992, 1994), thus reducing finger contact in completing the task.

In episodic tasks, increased average force levels during the solid condition as compared to the moving fluid condition would relate more to exertion than to movement accuracy. These results were consistent with data from Santello et al.(2004) where authors found significant increases in finger contact forces in predictable conditions, i.e., when there was no movement of COM than when it was unpredictable. They quantified the effect of COM location and its predictability on the fingertip forces, when participants lifted an apparatus whose COM location was changed from trial to trial in an unpredictable (random) order or predictable. Participants employed a wider range of forces when the object COM location was predictable than that found when it was unpredictable, on a trial to-trial basis. This suggests that subjects took advantage of a priori information about the object's COM location in a predictive fashion.

In episodic tasks, reduced average force levels were more often observed for fluid condition than solid perhaps was because fluid flow provides a real time sensory stimulation beyond that of solid, and thus the CNS can use this extra information to reduce effort. Although vision provides information about an object's mechanical properties for successful manipulation, in our study vision is of limited utility, as objects are out of sight and fluid motion could not be visualized.

Online feedback is especially critical when the CNS must stabilize inherently unstable or oscillatory objects (Johansson, 1998; Kuo, 2002).While manipulating a fluid-filled object about a vertical axis, then the gravitational and inertial loads will change in an unpredictable way as the object moves. Therefore, timely sensory feedback controls have a crucial role to play in taking rapid corrective action to accommodate these mechanical events and to minimize movement errors or slips. A recent study by Huang et al. (2010) has also shown that sensory feedback was needed when participants grasped the motorized handle, and operated the handle by using arm pronation and supination to excite and maintain maximum amplitude oscillations of the virtual inertia. The absence of sensory feedback severely compromised participants' ability to drive the resonant dynamics of an extrinsic mechanical system.

2. Effect of COM location (mode of manipulation)

Many objects used in our daily life are manipulated, by holding them either above the COM (such as drinking from a bottle) or by holding them below the COM (such as drinking from a cup glass or bottle) these are kind of the same example for 2 different COM's. Most of the studies to date (Wing & Lederman, 1998; Winges et al., 2007, 2008) have evaluated patterns of grip forces due to location of mass centre either during the hold phase of a lifting task or during a slow movement of the object using the elbow or wrist joint, in which case external destabilizing forces are minimal. Our study is an extension of these studies that examined the effect of COM location (P-mode vs IP-mode) on movement accuracy and finger contact force levels when participants manipulated two coffee cups, one with fluid one solid, with the thumb and index finger.

A. Movement Performance and Accuracy

a. Open loop task

In open-loop tracking tasks there was no difference discerned in movement performance while manipulating either solid or fluid objects. Quality of movement evaluated by the maximum cross-correlation coefficient (MCC) of the whole signal was not influenced by mode of manipulation. Movement accuracy evaluated by temporal and amplitude error at the turning points (endpoints) of the cyclic movements was also not influenced by mode of manipulation.

Similar to open-loop tracking tasks used in the present study, Kapadia et al. (2008) examined motor performance and movement accuracy while manipulating a light-weight cylinder in P-mode and IP-modes. It was shown that control of temporal organization and variation in spatial accuracy around the turning points did not depend on location of COM (pendular versus inverted pendular motion). Adults have extensive exposure to the dynamics of objects with varied COM locations, and for this reason, past experience could account for the lack of any effect of mode of manipulation on the temporal organization and variation in movement amplitude. With experience, we can quickly change patterns of muscle activation to adjust our grasp for differences in mass, moment of inertia, rigidity, or other mechanical properties. This ability is thought to depend on interaction between the human subject and the manipulated object (Flanagan & Wing, 1997; Kawato, 1999).

Consistent with these results, Lukos et al. (2007) have shown that implicit knowledge gained from past manipulations enabled subjects to modulate contact points and minimize roll. In a subsequent study they quantified the extent to which anticipatory control of grasping based on sensorimotor memories derived from previous manipulations (implicit knowledge) could be replaced by providing participants with explicit knowledge (visual and verbal cues) about COM. The spatial distribution of contact points was modulated when subjects had implicit knowledge of object COM location resulting from direct somatosensory information acquired through lifting the object. This knowledge allowed subjects to anticipate the necessary forces required to minimize object roll during lift. However, explicit knowledge of COM location did not enable object roll minimization (Lukos et al., 2008). Thus accurate sensorimotor memories depended on the acquisition of implicit knowledge about object properties associated with repeated manipulations of the same object in successful task performance.

Our findings were also consistent with the results of Dagmar et al., (2001) who observed that temporal and spatial accuracy at the turning points were not affected by the length and mass of a pendulum used to track a cyclic moving target Dagmar et al., (2001).

Salimi et al., (2000) showed that when grasping and lifting with a precision grip an object with an asymmetrical mass distribution, participants learned this task within two consecutive lifts by partitioning fingertip tangential forces asymmetrically prior to lift-off. This behavior results in generating a compensatory moment in the opposite direction of the external moment, thus minimizing object roll. These findings suggest that participants employed a feed-forward control strategy that accounts for the weight distribution of the object by appropriately partitioning the load force development between the two digits according to the COM location Salimi et al., (2000).

Similar findings have been observed by Gordon et al. (1993), Johansson and Flanagan (2009), and Johansson and Westling (1988). These studies showed that anticipatory control developed within just a few lifts of an object, and it relied on the ability to generate, store, and retrieve sensorimotor memories of previous actions associated with grasped objects.

As in the present study, which involved repeated trials of cyclic movements using irregular-shaped objects or objects with variable mass centre locations, one quickly adapts within a few trials or movement cycles and learns to predict complex gravity and motion dependant forces to significantly reduce spatial and temporal movement errors (Winges et al., 2008).

b. Closed loop Task

In predictable closed-loop tracking tasks, quality of movement evaluated by maximum cross-correlation coefficient (MCC) of whole-movement trajectory during cyclic movements was not influenced by P and IP mode. However, movement accuracy evaluated by temporal and amplitude error at the turning points (endpoints) of the cyclic movements was influenced by mode of manipulation.

One reason behind the decline in performance in the closed-loop tracking was this task required more visual attention and cognitive functions to track two objects instead of one and determination of the difference in absolute location of the slaved target relative to the computer motion-controlled cursor. Hence the participants made temporal and amplitude errors; thus there is a decline in their performance. Task complexity affects attention, accuracy, and the time needed to complete a trial (Ackerman, 1988; Ackerman, Beier, & Boyle, 2002; Verwey & Veltman, 1996).

When there is more focus on biofeedback, i.e., multiple tasks are involved, then more attention is required for that aspect and thus there may be a decrement in the motor output of the system. In study done by Sterr et al., (2009), participants were asked to trace a constantly changing target by adjusting their isometric grip-force output with a force device over a period of 30 seconds. Feedback accuracy was manipulated by varying the sensitivity of the target force range. The feedback was comprised of a vertical bar representing the force exerted and a horizontal bar representing the target force. The target bar turned green when the exerted force was within the set target range and turned red when the force dropped or exceeded that range. Task speed also varied either by tracking one cycle of a sine wave or tracking a zigzag course of several peaks. Performance was indexed as mean deviation (error) for each condition. More errors were made when feedback accuracy was higher than when it was low. Though more accurate feedback should enhance the motor output, there was a decline in the performance. This is because more accurate feedback provided more detailed information on the actual force output and therefore the need to correct the force output more frequently. This results in higher force irregularity when feedback is more accurate. This resulted in a greater number of errors as well as greater demand on brain regions involved in the task Sterr et al., (2009). .

In a study by Reed et al., (2003), participants were instructed to track a visual target moving horizontally across a screen with a visual cursor controlled by a joystick. Movements of the cursor represent rotation of the joystick during wrist flexion movement. As vertical separation of the target and movement cursors increased, the accuracy and intermittency (stopping and starting at irregular intervals) of the tracking movements decreased. The increased cursor separation reduced the ease and efficiency of making spatial comparisons of their positions, and thus the ability of the visual system to detect errors in the movement relative to the guiding target was undermined. In conclusion, this study confirms that the accuracy and intermittency of visually guided slow tracking movements are based on visual detection of error between the target and movement cursor positions. They have shown that when it is made more difficult to detect such errors by inserting a vertical separation between the cursors and hence inhibiting direct positional comparisons, the accuracy and intermittency in tracking are significantly reduced .Reed et al., (2003).

One reason for larger errors in IP-mode compared to P-mode likely occurred because, during pendulum motion, the gravitational force that decelerates a pendulum from its tilted position to vertical (equilibrium position) will re-accelerate the pendulum in the next half-cycle towards its maximum tilted position. Thus force control for the pendulum motion would be simplified due to gravity In contrast for IP-mode, no restoring forces are present, and gravity would increase object tilt from vertical in both primary and off-axis directions. Thus there would be a greater need for online feedback sensory signal to control motion and reversal at the turning points, and increased need to minimize off-axis motion.

c. Episodic task

In the case of episodic tasks conditions, our hypothesis "was rejected" because there was no change in movement performance as a function of mode of manipulation. As described for the open-loop condition, prior experience is mostly likely why we did not see an effect on movement performance due to location of COM.

Adults have extensive exposure to the dynamics of objects with varied COM locations, and for this reason past experience could account for the lack of any effect of mode of manipulation on the temporal organization and variation in movement amplitude.

Participants could have learned this task earlier as they manipulate these kinds of objects many times daily. While actually performing the task participants must have learned this task within two consecutive tilts and employed a feed-forward control strategy that accounts for the weight distribution of the object by appropriately partitioning the load-force development between the two digits according to the COM location. This was consistent with previous studies of cyclic manipulation of irregular-shaped objects paced by a moving visual target in which participants could quickly adopt within a few movement cycles and learned to predict complex gravity and motion-dependant forces (Russell & Sternad, 2001;Roerdink, Peper, & Beek, 2005; Roerdink, Ophoff, Lieke, Peper, & Beek, 2008 Salmi, Hollender, Frazier, & Gordon, 2000). Thus we extend these findings to include precision episodic ramp (slow) movements.

Another reason for no change in movement performance as a function of mode of manipulation perhaps would be that humans can learn in single trials to predict mass distribution of the object, rendering torques tangential to the grasped surfaces that challenge grasp stability in manipulatory maneuvers (Goodwin et al., 1998; Johansson et al., 1999).

In a recent study by Fu et al., (2010), when participants were asked to lift an object while minimizing roll caused by an external torque due to asymmetric mass distribution, they learned to compensate for asymmetric mass distribution and object roll within a few repeated trials. This was accomplished by generating a compensatory torque in the direction opposite to that caused by the added mass .Compensatory torque was used as a measure of learning anticipatory grasp control for object roll minimization .For successful object roll minimization to occur; participants had to learn to match the external torque with a compensatory torque of equal magnitude and opposite direction before the object is lifted. Therefore, subjects have to anticipate rather than react to the external torque. Fu et al. (2010)Consistent with previous studies of implicit learning of grasping within blocked trials, participants learned to minimize object roll within the first three trials by changing digit placement (Lukos et al., 2007, 2008). Participants can also learn to minimize object tilt by altering force distribution applied by the fingers (Salimi et al., 2000).

B. Magnitude of finger forces

Our study revealed that average digit-contact forces were not influenced when COM location is equally above and below digit-contact plane in both cyclic predictable and episodic tasks. One possible explanation for no change in finger-contact forces in our study was that within a few repetitive trials or continuous game events participants were able to learn a feed-forward control strategy to accommodate for different COM locations. This evidence can be supported by a recent study, Salmi et al., (2000) in which Participants lifted an object using a precision grip while the fingertip forces and the angle about the vertical axis (roll) were measured. The object's COM could be shifted to the left or right of the object's center parallel to the grip axis without changing its visual appearance. Within three to five lifts, participants were able to asymmetrically partition the load-force development before lift-off such that it was higher in the digit opposing the COM. This anticipatory load-force partitioning prevented the object from rolling sideways at lift-off. Their findings suggest that participants employ a feed-forward control strategy that accounts for the weight distribution of the object by appropriately partitioning the load-force development between the two digits according to the COM location Salmi et al., (2000) .This is also in agreement with other studies that show that grip forces are scaled based on the predicted torsional load when the center of mass is located distal to the grip axis joining the fingertips (Johansson et al., 1999; Wing & Lederman, 1998). Subjects scale their grip forces in anticipation of the resulting load torque. In their experiment, the load was equally distributed between the two opposing digits; i.e., the COM was located distal to the grip axis joining the fingertips (Wing and Lederman, 1998).However our results were contrary to those of Kapadia et al., (2008) who examined the effect of mode of manipulation on RMS of finger-contact forces. They found that there was a statistically significant effect on RMS of the thumb and finger forces in both P and IP mode of manipulation .However these results were confined only to an open loop task where participants viewed a brightly colored sinusoidally moving cursor on the monitor and were instructed to move the object in concert with the moving cursor. They found increase in forces only with small diameter objects (8cm) and was less with larger diameter objects,(15cm).The diameter of the objects used in our study was much bigger than Kapdia's study this has lead to decrease in finger forces. 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. These results are consistent with Goodwin et al., (1998) authors showed that as the surface curvature of object increased, and so did the grip forces (i.e. larger forces were required for the smaller objects diameter than for an object with a larger diameter).

CONCLUSION

In conclusion, this study revealed that for cyclic (predictable) open-loop and closed loop hand-tracking task and episodic short duration point-to-point movements to visual targets, which by the way are moderately complex and require precision, healthy young adults have high performance levels, i.e., have little difficulty in performance levels irrespective of a moving COM or whether performing eccentric/concentric movements against gravity (IP-mode) or concentric movements with gravity assistance (P-mode).

Key study findings

1. Effect of Moving Mass centre:

A. On movement performance and movement accuracy

a) In predictable tasks (No change)

b) In episodic task. (No change)

B. On finger contact forces

No change in predictable task however Finger contact forces increased while manipulating solid cup compared to liquid cup in episodic task.

2. Effect of Location of mass centre: (P-mode versus IP-mode)

A. On movement performance and movement accuracy

a) Open loop task (No change)

b) Closed loop task (temporal and amplitude errors increased)

c) Episodic task (No change)

B. On finger contact forces

(No change in both predictable and episodic task)

Interaction effect: No interaction effect was found

Clinical Significance

Manipulating an object is a complex goal-directed behavior that requires sensory, executive cognitive, and motor processes through feed-forward and feedback controls. Executive and cognitive functions describe a loosely defined collection of brain processes that are responsible for planning, initiating appropriate actions and inhibiting inappropriate actions, and selecting relevant sensory information Neuro-adaptation leading to recovery of function emerges from learning feed-forward commands as well as improvements in feedback control. This is particularly important in rehabilitation of fine motor skills to accommodate handling and manipulation of objects with a wide range of physical properties.

Performance of fine motor function is dependent 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 COM relative to the point of finger contact. Objective quantification of such clinically relevant changes in motor control in hand is necessary to document the impact of neuromuscular and skeletal injuries on manual dexterity and hand function.

This study involves manipulation of fluid-filled objects with fingers that simulates more closely our daily activities like pouring liquids from one container to other or holding a wine glass. Thus this study can be extended to individuals with neurological and musculoskeletal disorders/injuries that face challenges in daily activities thus they can learn timely tactile sensory feedback and rapid corrective movements to prevent slips and unwanted spills.

Future Implications

In future studies, an analysis to look at the correlation between object motion and finger force profiles may provide better understanding of how the finger forces vary with object movement. (Frequency analyses), A power spectrum analysis will be carried out for both object motion data and finger force data in future studies may enable us to view object instabilities and the role of feedback processes in predictable rhythmic visuo-motor tracking tasks performed using precision grip. Power spectrum analysis will be computed using a Welch's averaged peridogram method. (Matlab V4.0)

Lightweight fluid-filled objects with 325 ml cold water measuring 6.5 in. were used in this study. Since many of the fluid-filled objects used in everyday life weigh more than 325 ml, it may be beneficial to determine the effects of higher height and weight fluid-filled objects on motor performance and spatial temporal variability. It would also be interesting to determine when it becomes essential to change from a 3-digit to whole-hand grip.

REFERENCES

Adams, J. A. (1987). Historical review and appraisal of research on the learning, retention and transfer of human motor skills. Psychological Bulletin, *101*, 41–74.

Andersen Hammond, E. R., Szturm, Tony, & Shay, Barbara L. (2010). Manipulation of objects with and without the use of the index finger: Implications for digital amputations. *Journal of Hand Therapy*, *23*(4), 352-360.

Andersen Hammond ER, Shay BL, & Szturm T. (2009) Objective evaluation of fine motor manipulation: A new clinical tool J American Hand Therapy 22(1), 28-36.

Armbrüster, C., & Spijkers, W. (2006). Movement planning in prehension: Do intended actions influence the initial reach and grasp movement? *Motor Control*, *10*(4), 311-329.

Augurelle, A.S., Smith, A. M., Lejeune, T., & Thonnard, J. L. (2003). Importance of cutaneous feedback in maintaining a secure grip during manipulation of hand-held objects. *Journal of Neurophysiology*, *89*(2), 665-671.

Beek, P. J., Turvey, M. T., & Schmidt, R. C. (1992), Autonomous and nonautonomous dynamics of coordinated rhythmic movements. *Ecological Psychology*, *4*, 65–95.

Blake, R., Cepeda, N. J., & Hiris, E. (1997). Memory for visual motion. *Journal of Experimental Psychology: Human Perception and Performance, 23*(2), 353-369.

Blakemore, S. J., Goodbody, S. J., & Wolpert, D. M. (1998). Predicting the consequences of our own actions: The role of sensorimotor context estimation. *Journal of Neuroscience*, *18*(18), 7511–7518.

Brouwer, Anne-Marie, Middelburg, Tom, Jeroen, B., Smeets, J., & Brenner, Eli. (2003) Hitting moving targets: A dissociation between the use of the target's speed and direction of motion. *Experimental Brain Research, 152*, 368–375.

Byblow, W. D., Carson, R. G., & Goodman, D. (1994). Expressions of asymmetries and anchoring in bimanual coordination. *Human Movement Science, 13*(1), 3–28.

Brenner, E., & Smeets, J. B. (1996). Hitting moving targets: Co-operative control of 'when' and 'where.' *Human Movement Science*, *15*(1), 39-53.

Carey, J. R., Greer, K. R., Grunewald, T. K, Steele, J. L., Wiemiller, J. W., Bhatt, E. … Auerbach, Edward J. (2006). Primary motor area activation during precision-demanding versus simple finger movement. *Neurorehabilitation & Neural* Repair, *20*(3), 361-370.

Carey, J. R., Kimberley, T. J., Lewis, S. M., Auerbach, Edward J., Dorsey, Lisa, Rundquist, Peter, & Ugurbil, Kamil. (2002b). 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. *Physical Therapy*, *68*(7), 1087-1091.

Carnahan, H., Roy, E. A., Whiteside, R., & Ambis, C. (1998). Time delays between the presentation of visual information about moving targets and movement initiation do not alter interception kinematics. *Journal of Sport and Exercise Psychology, 20*, s37.

Carson, R. G. (1996). Neuromuscular-skeletal constraints upon the dynamics of perception-action coupling. *Experimental Brain Research, 110*, 99–110.

Carson, R. G., & Riek, S. (1998). The influence of joint position on the dynamics of perception-action coupling. *Experimental Brain Research*, *121*, 103–114.

Cisek, P. (2005). Neural representations of motor plans, desired trajectories, and controlled objects. *Cognitive Processing*, *6*, 15–24.

Cordo, P. J., & Flanders, M. (1989). Sensory control of target acquisition. *Trends in Neurosciences*, *12*(3), 110-117. Review.

Castiello, U., & Jeannerod, M. (1991) Measuring time to awareness. *NeuroReport*, *2*, 797-800.

Castiello U., Paulignan, Y., & Jeannerod, M. (1991). Temporal dissociation of motor responses and subjective awareness. *Brain*, *114*, 2639-2655.

Cooke, J. D., & Diggles, V.A. (1984). Rapid error correction during human arm movements: Evidence for central monitoring. *Journal of Motor Behavior, 16*(4), 348–363.

Chabran, E., Maton, B., Ribreau, C., & Fourment, A. (2001). Electromyographic and biomechanical characteristics of segmental postural adjustments associated with voluntary wrist movements: Influence of an elbow support. *Experimental Brain Research*, *141*(2), 133–145.

Chan, T. C. (1995). The effect of density and diameter on haptic perception of rod length. *Perception and Psychophysics, 57*(6), 778–786.

Dartnall, T. J., Jaberzadeh, S., Miles, T. S., & Nordstrom, M. A. (2009). Motor training decreases finger tremor and movement response time in a visuomotor tracking task. *Journal of Motor Behavior*, *41*(1), 55-64.

Dubrowski, A., & Carnahan, H. (2001). Control strategies when intercepting slowly moving targets. *Journal of Motor Behavior, 33*(1), 37-48.

Dumont, C. E., Popovic, M. R., Keller, T., & Sheikh, R. (2006). Dynamic force-sharing in multi-digit task. *Clinical Biomechanics, 21*(2), 138–146.

Diedrichsen, J., Verstynen, T., Lehman, S. L., & Ivry, R. B. (2005). Cerebellar involvement in anticipating the consequences of self-produced actions during bimanual movements. *Journal of Neurophysiology, 93*(2), 801–812.

Danion, Frederic, & Sarlegna, Fabrice R. (2007). Can the human brain predict the consequences of arm movement corrections when transporting an object? Hints from grip force adjustments. *Journal of Neuroscience, 27*(47), 12839 –12843.

Eastough, D., & Edwards, M. G. (2007). Movement kinematics in prehension are affected by grasping objects of different mass. *Experimental Brain Research*, *176*(1), 193-198.

Eric R.Kandel, James Schwartz, and Thomas Jessell. (2000). *Principles of Neural Science*. (Fourth edition)

Fabrice, Sarlegna., Jean, Blouin., Jean-Pierre, Bresciani., Christophe.Bourdin., Jean-Louis Vercher&, Gabriel M. Gauthier. (2003). Target and hand position information in the online control of goal-directed arm movements. *Experimental Brain Research, 151*(4), 524–535.

Fitts, P. M. (1964). Perceptual-motor skill learning. In A. W. Melton (Ed.), *Categories of human learning* (pp. 243-285). London: Academic Press.

Flanagan, J. R., Burstedt, M. K., & Johansson, R. S. (1999). Control of fingertip forces in multidigit manipulation. *Journal of Neurophysiology*, *81*(4), 1706-1717.

Flanagan, J. R., Vetter, P., Johansson, R, S., & Wolpert, D, M. (2003).Prediction precedes control in motor learning. *Current Biology*, *13*(2), 146-150.

Flanagan, J. R., & Wing, A. M. (1993). Modulation of grip force with load force during point-to-point arm movements. *Experimental Brain Research*, *95*(1), 131-143.

Flanagan, J. R., & Wing, A. M. (1995). The stability of precision grip force during cyclic arm movements with a hand-held load. *Experimental Brain Research, 105*, 455-464.

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. *Journal of Neuroscience*, *17*(4), 1519–1528.

Flanders, M., & Cordo, P. J. (1989). Kinesthetic and visual control of a bimanual task: Specification of direction and amplitude. *Journal of Neuroscience, 9*(2), 447-453.

Foulkes, A. J., & Miall, R. C. (2000). Adaptation to visual feedback delays in a human manual tracking task. *Experimental Brain Research*, *131*(1), 101-110.

Fu, Qiushi, Zhang, Wei, & Santello, Marco. (2010). Anticipatory planning and control of grasp positions and forces for dexterous two-digit manipulation. *Journal of Neuroscience*, *30*(27), 9117–9126.

Fuchs, A. H. (1962). The progression-regression hypothesis in perceptual-motor skill learning. *Journal of* Experimental Psycholo*gy, 63*, 177–182.

Gao, F., Latash, M. I., & Zatsiorsky, V. M. (2005). Internal forces during object manipulation. *Experimental Brain Research, 165*(1), 69-83.

Garvey, W. D. (1960). A comparison of the effects of training and secondary tasks on tracking behaviour. *Journal of* Applied Psychology, *44*(6), 370–375.

Georgopoulos, A. P. (2000). Neural aspects of cognitive motor control. *Current Opinion in Neurobiology*, *10*(2), 238–241.

Goodale, M. A., Peusson, & D., Prablanc., C. (1986). Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature, 320*, 748-750.

Goodwin, A. W., Jenmalm, P. & Johansson, R. S. (1998). Control of grip force when tilting objects: Effect of curvature of grasped surfaces and applied tangential torque. *Journal of Neuroscience, 18*(24), 10724-10734.

Gordon, Andrew M., Westling, Goran, Cole, Kelly J., & Johansson, Roland S. (1993). Memory representations underlying motor commands used during manipulation of common and novel objects. *Journal of Neurophysiology, 69*(6), 1789-1796.

Grafton, S. T., Schmitt, P., Van Horn, J., & Diedrichsen J. (2008). Neural substrates of visuomotor learning based on improved feedback control and prediction. *NeuroImage, 39*(3), 1383-1395.

Hager-Ross, C., & Johansson, R. S. (1996). Non digital afferent input in reactive control of fingertip forces during precision grip. *Experimental Brain Research, 110*(1), 131-141.

Hammerton, M. (1989). Tracking. In D. H. Holding (Ed.), *Human skills* (2nd ed.) (pp. 171-195). Chichester, UK: Wiley.

Hermsdorfer, J. & Blankenfeld, H. (2008). Grip force control of predictable external loads. *Experimental Brain Research, 185*(7), 719–728.

Hermsdorfer, J., Hagl, E., Nowak, D. A., & Marquardt, C. (2003). Grip force control during object manipulation in cerebral stroke. *Clinical Neurophysiology, 114*(5), 915-929.

Hou, W., Zheng, J., Jiang, Y., Shen, S., Sterr, A., Szameitat, A. J., & Van Loon, M. (2006). A behaviour study of the effects of visual feedback on motor output.

Conference Proceedings of the IEEE Engineering in Medicine and Biology Society, *1*, 1273-1276.

Huang, F. C., Gillespie, R. B., Kuo, A. D. (2010). Visual and haptic feedback contribute to tuning and online control during object manipulation. *Journal of Motor Behavior*. *39*(3), 179-193

Hund-Georgiadis, M., & VonCramon, D. Y. (1999). Motor-learning-related changes in piano players and non-musicians revealed by functional magnetic-resonance signals. *Experimental Brain Research*, *125*(4), 417-425.

Jenmalm, P., Dahlstedt, Seth, & Johansson, Roland S. (2000). Visual and tactile information about object-curvature control fingertip forces and grasp kinematics in human dexterous manipulation. *Journal of Neurophysiology*, *84*, 2984–2997.

Jenmalm, P., Goodwin, A. W., & Johansson, R. S. (1998). Control of grasp stability when humans lift objects with different surface curvatures. *Journal of Neurophysiology*, *79*, 1643–1652.

Jenmalm, P., & Johansson, R. S. (1997). Visual and somatosensory information about object shape control manipulative fingertip forces. *Journal of Neuroscience, 17*(11), 4486-4499.

Johansson, R. S. (1999). Sensory input and control of grip. *Novartis Foundation symposium*, *218*, 45-59.

Johansson, R. S., & Cole, K. J. (1992). Sensory-motor coordination during grasping and manipulative actions. *Current Opinion in Neurobiology*, *2*(6), 815-823.

Johansson, R. S., & Cole, K. J. (1994). Grasp stability during manipulative actions. Canadian *Journal of Physiology and Pharmacology*, *172*(5), 511-524.

Johansson, R. S., & Flanagan, J. R. (2009a). Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nature Reviews Neuroscience*, *10*, 345-359.

Johansson, R. S., & Flanagan, J. R. (2009b). Sensorimotor control of manipulation. *Encyclopedia of Neuroscience, 8*, 593-604.

Johansson, R. S., Hager, C., & Backstrom, L. (1992). Somatosensory control of precision grip during unpredictable pulling loads. II. Impairments during digital anesthesia. *Experimental Brain Research*, *89*(1), 204-213.

Johansson, R. S., Hager, C., & Riso, R. (1992). Somatosensory control of precision grip during unpredictable pulling loads. II. Changes in load force rate. *Experimental Brain Research, 89*(1), 192-203.

Johansson, R. S., Riso, R., Hager, C., & Backstrom, L. (1992). Somatosensory control of precision grip during unpredictable pulling loads. I. Changes in load force amplitude. *Experimental Brain Research, 89*(1), 181-191.

Johansson, R. S., & Westling, G. (1984). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research*, *56*(3), 550-564.

Johansson, R. S., & Westling, G. (1988). Programmed and triggered actions to rapid load changes during precision grip. *Experimental Brain Research, 71*(1), 72-86.

Johnson-Frey, S. H. (2004). The neural bases of complex tool use in humans. *Trends in Cognitive Science, 8*(2), 71-78.

Jordan, K., Newell, K. M. (2004). Task goal and grip force dynamics. *Experimental Brain Research*, *156*(4), 451-457.

Kapadia, N. (2008). *Effect of geometric properties and varying torque levels on movement accuracy and grip force pattern during object manipulation* (Master's thesis). University of Manitoba, Canada.

Kawashima, R., Matsumura, M., Sadato, N., Naito, E., Waki, A., Nakamura S. … Yonekura, Y. (1998). Regional cerebral blood flow changes in human brain related to ipsilateral and contralateral complex hand movements: A PET study. *European Journal of Neuroscience, 10*(7), 2254-2260.

Kawato, M. (1996). Learning internal models of the motor apparatus. In James Bloedel & Timothy J. Ebner (Eds.), *The acquisition of motor behavior in vertebrates* (pp. 409-430). MIT Press.

Kinoshita, H., Backstrom, L., Flanagan, J. R., & Johansson, R. S. (1997). Tangential torque effects on the control of grip forces when holding objects with a precision grip. *Journal of Neurophysiology, 78*(3), 1619-1630.

Kriz, G., Hermsdörfer, J., Marquardt, C., & Mai, N. (1995). Feedback-based training of grip force control in patients with brain damage. *Archives of Physical Medicine and Rehabilitation, 76*(7), 653-659.

Kuo, A. D. (2002). The relative roles of feed forward and feedback in the control of rhythmic movements. *Motor Control, 6*(2), 129–145.

Langenberg, U., Hefter, H., Kessler, K. R., & Cooke, J. D. (1998). Sinusoidal forearm tracking with delayed visual feedback. I. Dependence of the tracking error on the relative delay. *Experimental Brain Research*, *118*(2), 161-170.

Lee, D. N., Georgopoulos, A. P., Clark, M. J., Craig, C, M., & Port, N. L. (2001). Guiding contact by coupling the taus of gaps. *Experimental Brain Research*, *139*(2), 151–159.

Luft, A. R., & Buitrago, M. M. (2007). Stages of motor skill learning. *Molecular Neurobiology*, *32*(3), 205-216.

Lukos, J. R., Ansuini, C., & Santello, M. (2007). Choice of contact points during multidigit grasping: Effect of predictability of object center of mass location. *Journal of Neuroscience*, *27*(14), 3894-3903.

Lukos, J. R., Ansuini, C., & Santello, M**.** (2008). Anticipatory control of grasping: Independence of sensorimotor memories for kinematics and kinetics. *Journal of Neuroscience*, *28*(48), 12765-12774.

Macefield, V. G., & Johansson, R. S. (1996). Control of grip force during restraint of an object held between finger and thumb: Responses of muscle and joint afferents from the digits. *Experimental Brain Research*, *108*(1), 172-184.

Maslovat, D., Chua, R., Lee, T. D., & Franks, I. M. (2006). Anchoring strategies for learning a bimanual coordination pattern. *Journal of Motor Behavior*, *38*(2), 101–117.

Mason, C. R., Gomez, J. E., & Ebner, T. J. (2001). Hand synergies during reach-to-grasp. *Journal of Neurophysiology*, *86*(6), 2896-2910.

McDonnell, M. N., Ridding, M. C., Flavel, S. C., & Miles, T. S. (2005). Effect of human grip strategy on force control in precision tasks. *Experimental Brain Research*, *161*(3), 368-373.

Merchant, H., Zarco, W., Prado, L., & Perez, O. (2009). Behavioral and neurophysiological aspects of target interception. *Advances in Experimental Medicine and Biology, 629*(pt 2), 201-220.

Miall, R. C., Weir, D. J., & Stein, J. F. (1985). Visuomotor tracking with delayed visual feedback. *Neuroscience, 16*(3), 511–520.

Miall, R. C., & Wolpert, D. M. (1996). Forward models for physiological motor control. *Neural Networks*, *9*(8), 1265-1279.

Mrotek, L. A., & Soechting, J. F. (2007). Target interception: Hand-eye coordination and strategies. *Journal of Neuroscience*, *27*(27), 7297-7309.

Nowak, D. A., Glasauer, S., & Hermsdorfer, J. (2003). Grip force efficiency in long-term deprivation of somatosensory feedback. *NeuroReport*, *14*(14), 1803-1807.

Nowak, D. A., Glasauer, S., & Hermsdorfer, J. (2004). How predictive is grip force control in the complete absence of somatosensory feedback? *Brain*, *127*(pt 1), 182-192.

Nowak, D. A., & Hermsdorfer, J. (2005). Grip force behaviour during object manipulation in neurological disorders: Toward an objective evaluation of manual performance deficits. *Movement Disorders, 20*(1**), 11-25**.

Nowak, D. A., Hermsdorfer, J., Marquardt, C., & Fuchs, H. H. (2002). Grip and load force coupling during discrete vertical arm movements with a grasped object in cerebellar atrophy. *Experimental Brain Research*, *145*(1), 28–39.

Ohki, Y., Edin, B. B., & Johansson, R. S. (2002). Predictions specify reactive control of individual digits in manipulation. *Journal of Neuroscience, 22*(2), 600–610.

Otto, C.: Magnetic motion tracking system for interactive gaming. *Master's thesis,*

Department of Electronic & Computer Engineering (2007).
URL http://wren.ece.umanitoba.ca/

Paulignan, Y., Mackenzie, C., Marteniuk, R., & Jeannerod, M. (1991). Selective perturbation of visual input during prehension movements. I. The effects of changing object position. *Experimental Brain Research*, *83*(3), 502-512.

Pisella, L., Gr´ea, H., Tilikete, C., Vighetto, A., Desmurget, M., Rode, G. … Rossetti, Y. (2000). An automatic pilot for the hand in the posterior parietal cortex: Toward a reinterpretation of optic ataxia. *Nature Neuroscience*, *3*(7), 629–636.

Port, N. L., Lee, D., Dassonville, P., & Georgopoulos, A. P. (1997). Manual interception of moving targets. I. Performance and movement initiation. *Experimental Brain Research*, *116*(3), 406–420.

Poulton, E. C. (1974). *Tracking skill and manual control*. New York: Academic Press.

Pylatiuk, C., Kargov, A., Schulz, S., & Doderlein, L. (2006). Distribution of grip force in three different functional prehension patterns. *Journal of Medical Engineering and Technology*, *30*(3), 176-182.

Rearick, M. P., & Santello, M. (2002). Force synergies for multifingered grasping: Effect of predictability in object center of mass and handedness. *Experimental Brain Research*, *144*(1)**,** 38–49.

Reed, Daniel W., Liu, Xuguang, & Miall, R. Christopher. (2003). On-line feedback control of human visually guided slow ramp tracking: Effects of spatial separation of visual cues. *Neuroscience Letters*, *338*(3), 209–212.

Roerdink, M., Ophoff, E. D., Lieke, E., Peper, C., & Beek, P. J. (2008). Visual and musculoskeletal underpinnings of anchoring in rhythmic visuo-motor tracking. *Experimental Brain Research*, *184*(2), 143-156.

Roerdink, M., Peper, C. E., & Beek, P. J. (2005). Effects of correct and transformed visual feedback on rhythmic visuo-motor tracking: Tracking performance and visual search behaviour. *Human Movement Science*, *24*(3), 379–402.

Russell, D. M., & Sternad, D. (2001). Sinusoidal tracking: Intermittent control or coupled oscillations? *Journal of Motor Behavior, 33*(4), 329–349.

Salimi, I., Hollender, I., Frazier, W., & Gordon, A. M. (2000). Specificity of internal representations underlying grasping. *Journal of Neurophysiology*, *84*(5), 2390-2397.

Santello, M., Flanders, M., & Soechting, J. F. (1998). Postural hand synergies for tool use. *Journal of Neuroscience*, *18*(23), 10105–10115.

Santello, M., Muratori, L., & Gordon, A. M. (2004). Control of multidigit grasping in Parkinson's disease: Effect of object property predictability. *Experimental Neurology*, *187*(2), 517-528.

Sarlegna, Fabrice R., Baud-Bovy, Gabriel, & Danion, Frédéric (2010). Delayed visual feedback affects both manual tracking and grip force control when transporting a handheld object. *Journal of Neurophysiology*, *104*(2), 641–653.

Saunders, J. A., & Knill, D. C. (2004). Visual feedback control of hand movements. *Journal of Neuroscience*, *24*(13), 3223-3234.

Schmitz, Christina, Jenmalm, Per, Ehrsson, H. Henrik, & Forssberg, Hans. (2005). Brain activity during predictable and unpredictable weight changes when lifting objects.

Journal of Neurophysiology, 93(3), 1498–1509.

Schenk, T., Walther, E. U., & Mai, N. (2000). Closed- and open-loop handwriting performance in patients with multiple sclerosis. *European Journal of Neurology, 7*(3), 269-279.

Seidler, R. D., Noll, D. C., & Thiers, G. (2004). Feed forward and feedback processes in motor control. *NeuroImage*, *22*(4), 1775-1783.

Shim, J. K., Latash, M. L., Zatsiorsky, V. M. (2005). Prehension synergies in three dimensions. *Journal of Neurophysiology, 93*(2), 766–776.

Smith, M. A., Ghazizadeh, A., & Shadmehr, R. (2006). Interacting adaptive processes with different timescales underlie short-term motor learning. PLoS Biology, *4*(6), e179.

Smith, M. A., & Soechting, J. F. (2005)**.** Modulation of grasping forces during object transport. *Journal of Neurophysiology*, *93*(1), 137-145.

Soechting, J. F., & Lacquaniti, F. (1983). Modification of trajectory of a pointing movement in response to a change in target location. *Journal of Neurophysiology*, *49*(2), 548-564.

Song, Joo-Hyun, & Nakayama, Ken. (2008). Target selection in visual search as revealed by movement trajectories. *Vision Research*, *48*(7), 853–861.

Sterr, A., Shen, S., Kranczioch, C., Szameitat, A. J., Hou, W., & Sorger, B. (2009). fMRI effects of task demand and feedback accuracy on grip force tracking. *Neuroscience Letters*, *457*(2), 61-65.

Talati, A., Valero-Cuevas, F. J., & Hirsch, J. (2005).Visual and tactile guidance of dexterous manipulation tasks: An fMRI study. *Perceptual Motor Skills*, *101*(1), 317-334.

Teulings, H. L. (1996). Handwriting movement control. In S.W. Keele & H. Heuer (Eds.), *Handbook of perception and action, Vol. 2, Motor skills* (pp. 561-613). London: Academic Press.

Van Donkelaar, P., Lee, R. G., & Gellman, R. S. (1992). Control strategies in directing the hand to moving targets. *Experimental Brain Research, 91*(1), 151-161.

Weir, D. J., Stein, J. F., & Miall, R. C. (1989). Cues and control strategies in visually guided tracking. *Journal of Motor Behavior*, *21*(3), 185-204.

Vercher, J. L., & Gauthier, G. M. (1992). Oculo-manual coordination control: Ocular and manual tracking of visual targets with delayed visual feedback of the hand motion. *Experimental Brain Research*, *90*(3), 599–609.

Westling, G., & Johansson, R. S. (1984). Factors influencing the force control during precision grip. *Experimental Brain Research, 53*(2), 277-284.

Wickens, C. D. (1992). *Engineering psychology and human performance* (2nd ed.). New York: HarperCollins.

Wing, A. M., & Lederman, S. J. (1998). Anticipating load torques produced by voluntary movements. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(6), 1571-1581.

Winges, S. A., Soechting, J. F., & Flanders, M. (2007). Multi-digit control of contact forces during transport of handheld objects. *Journal of Neurophysiology*, *98*(2), 851-860.

Winges, S. A., Soechting, J. F., & Flanders, M. (2008). Multi-digit control of contact forces during rotation of a handheld object. *Journal of Neurophysiology*, *99*(4), 1846-1856.

Winstein, C. J., Merians, A. S., & Sullivan, K. J. (1999). Motor learning after unilateral brain damage. *Neuropyschologia, 37*(8), 975-987.

Wise, S. P., Boussaoud, D., Johnson, P. B., & Caminiti, R. (1997). Premotor and parietal cortex: Corticocortical connectivity and combinatorial computations. *Annual Review of Neuroscience, 20*, 25–42.

Wolchik, S. A., West, S. G., Sandler, I. N., Tein, J., Coatsworth, D., Lengua, L. Griffin, W. A. (2000). An experimental evaluation of theory-based mother and mother-child programs for children of divorce. *Journal of Consulting and Clinical Psychology*, *68*(5), 843–845.

Yamanaka, H., Kawahira, K., Arima, M., Shimodozono, M., Etoh, S., Tanaka, N., & Tsujio, S. (2005). Evaluation of skilled arm movements in patients with stroke using a computerized motor-skill analyser for the arm. *International Journal of Rehabilitation Research*, *28*(3), 277–283.

Zatsiorsky, V. M., Gao, F., & Latash, M. L. (2003). Prehension synergies: Effects of object geometry and prescribed torques. *Experimental Brain Research, 148*(1), 77–87.

Zatsiorsky, V. M., Gao, F., & Latash, M. L. (2005). Motor control goes beyond physics: Differential effects of gravity and inertia on finger forces during manipulation of hand-held objects. *Experimental Brain Research*, *162*(3), 300-308.

Zatsiorsky, V. M., & Latash, M. L. (2004). Prehension synergies. *Exercise and Sport Sciences Reviews*, 32: 75–80.

APPENDICES

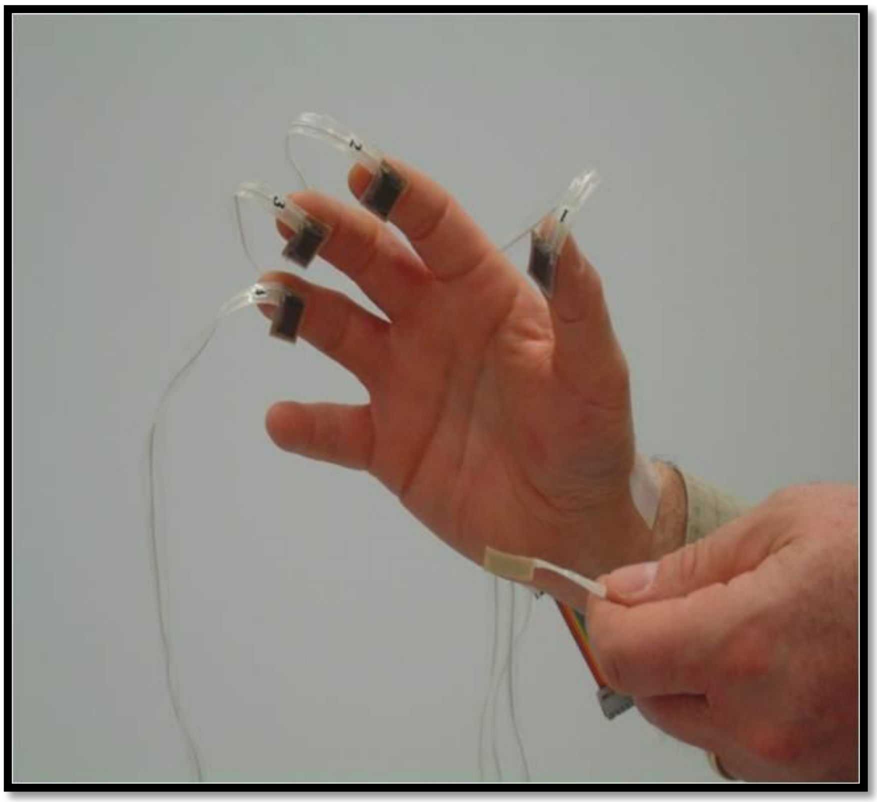
LIST OF FIGURES

Figure1: Objects used in the study

Solid **liquid**

Figure2: Minibird™ Motion tracker

Figure3: Finger Force sensors



:

Figure4: Experimental setup

Figure5: Modes of manipulation used in the study

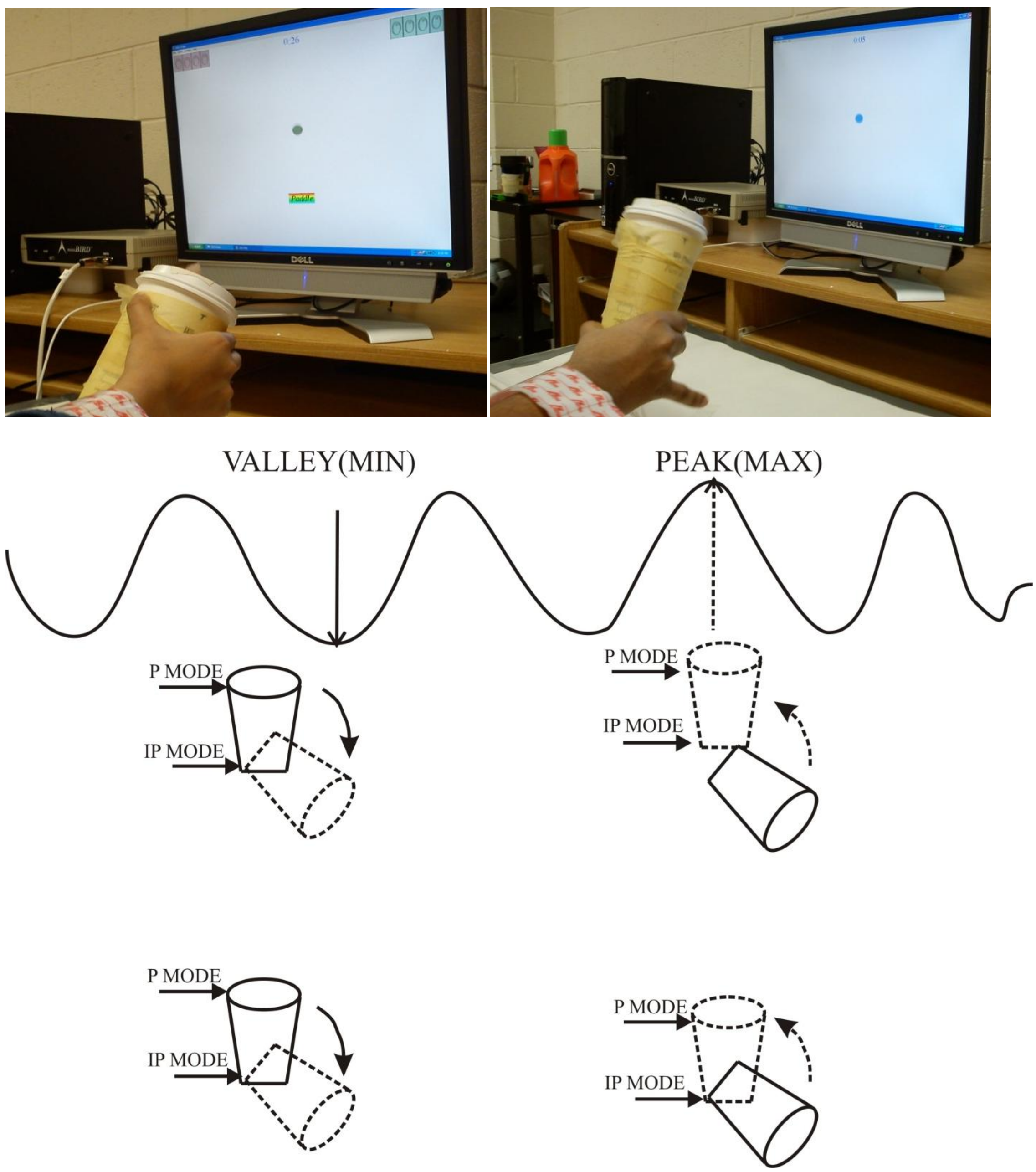


Figure6: Open loop Task

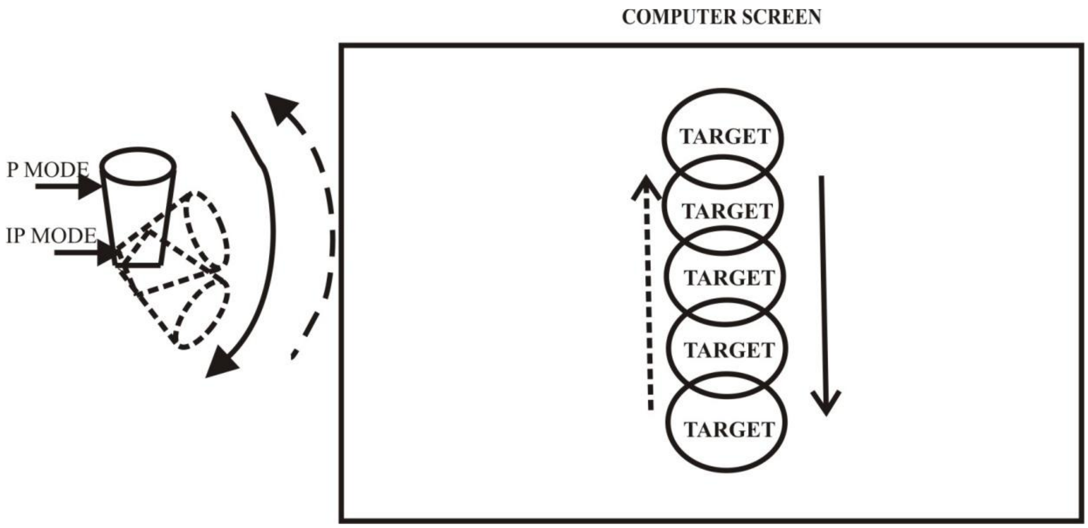


Figure7: Closed loop task

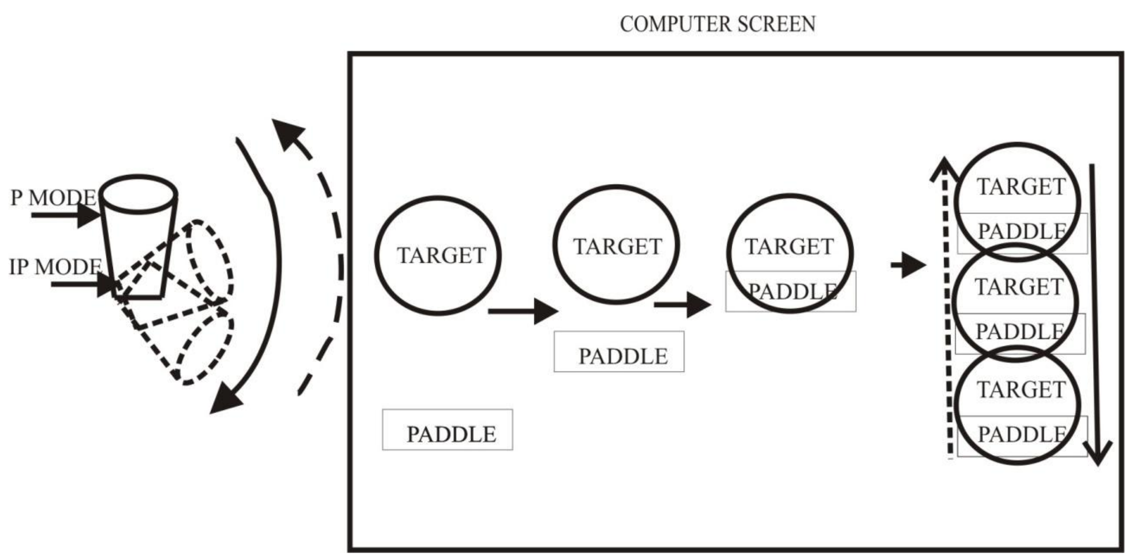


Figure8: Episodic task

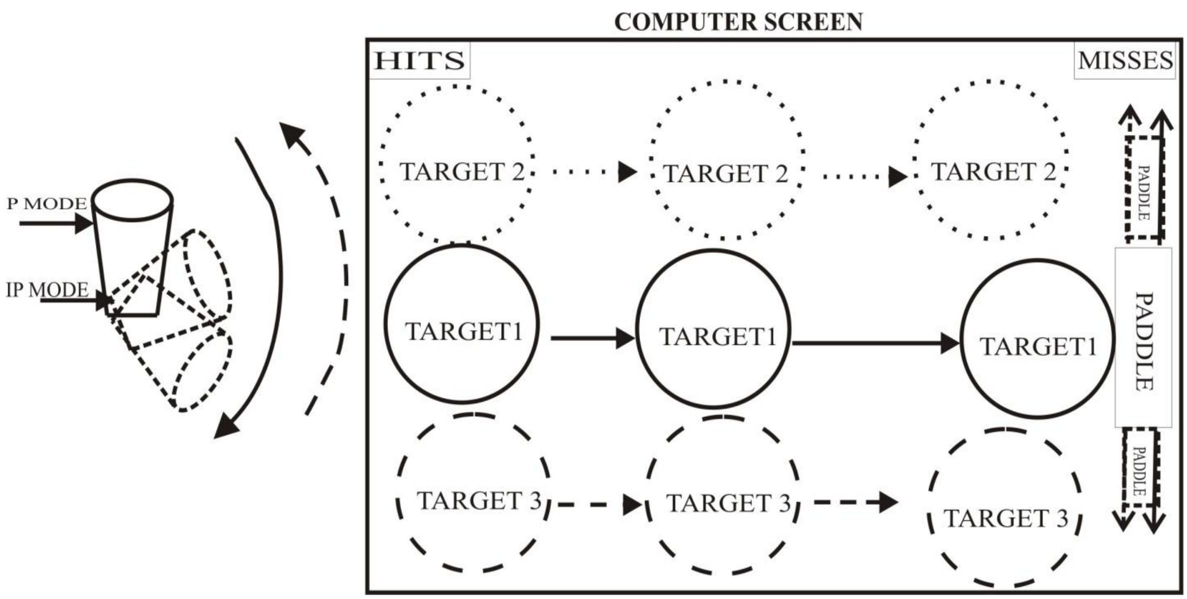


Figure9: Raw data from Episodic task

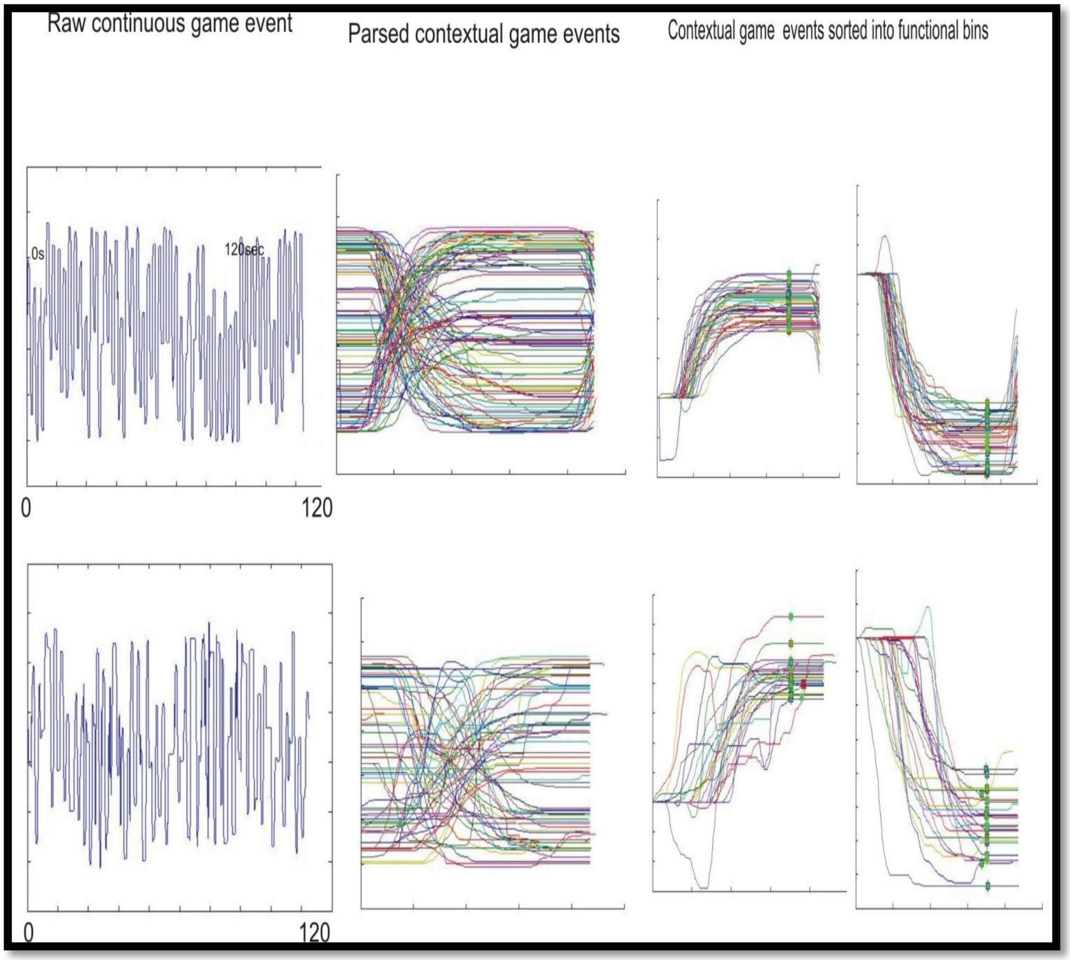


Figure10: Analysis of temporal and amplitude consitency

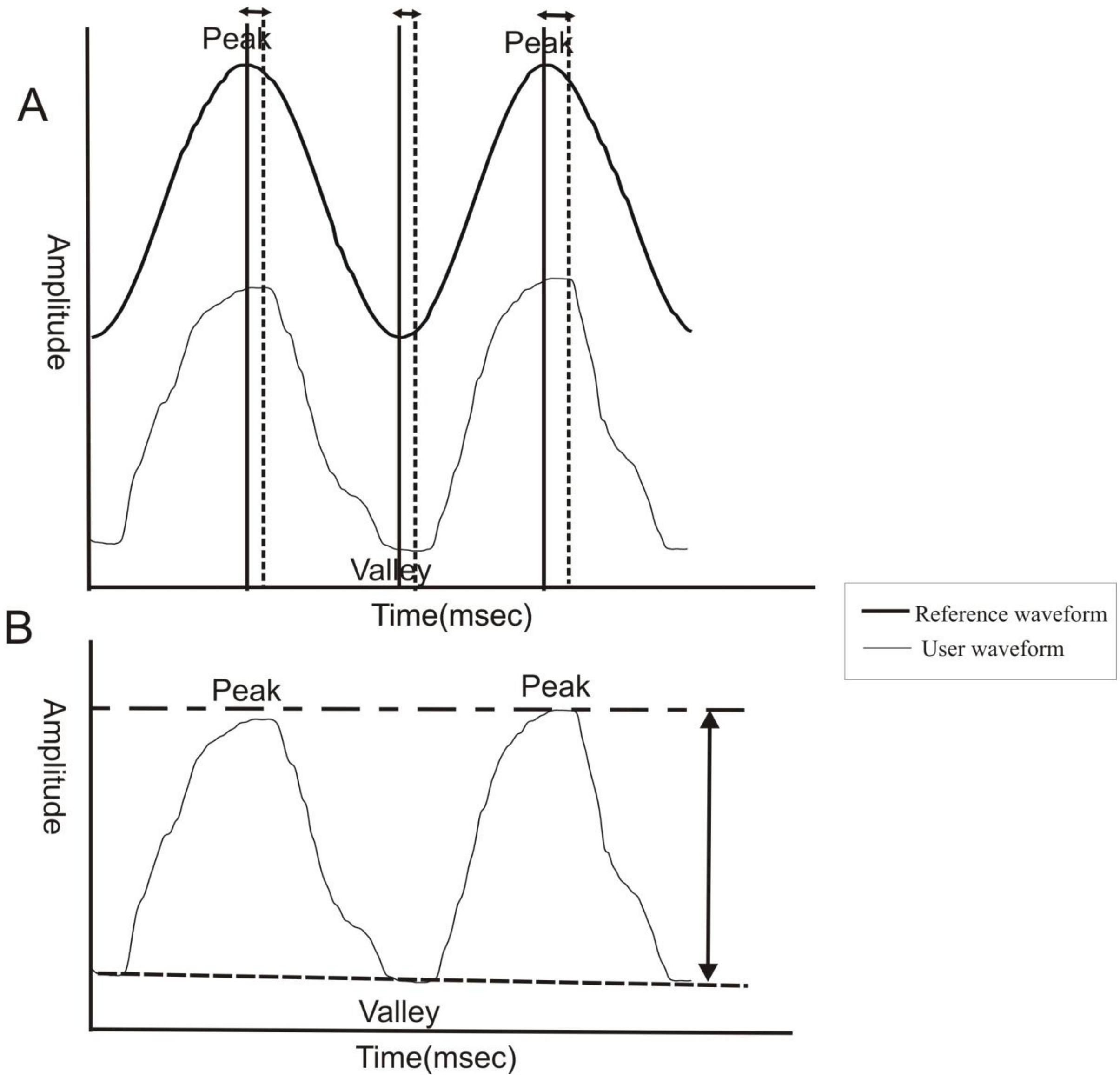


Figure11: Analysis of motor performance from episodic task

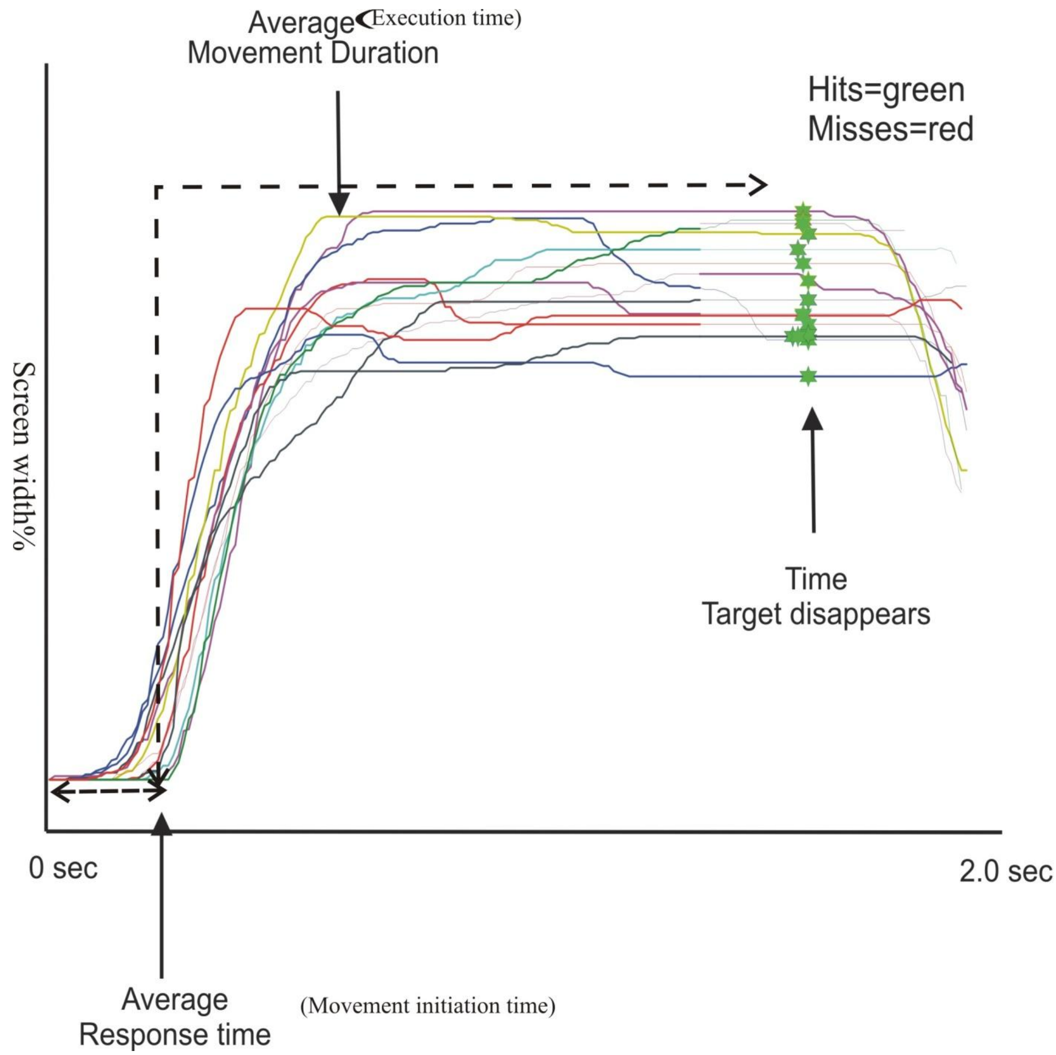


Figure12: Raw data figure of movement trajectory and finger-force profiles in open-loop task

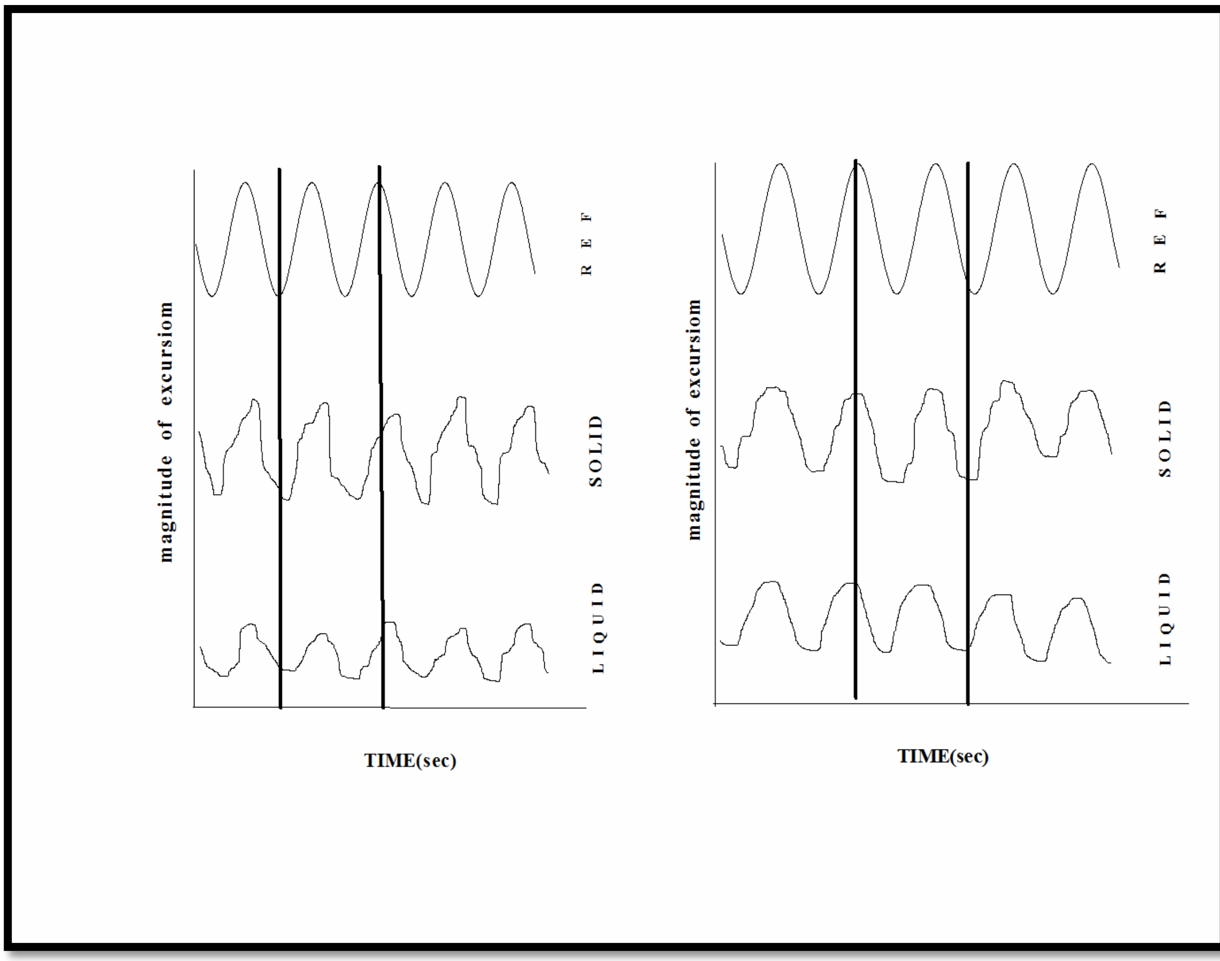


Figure13. Raw data figure of movement trajectory and finger-force profiles in closed-loop task

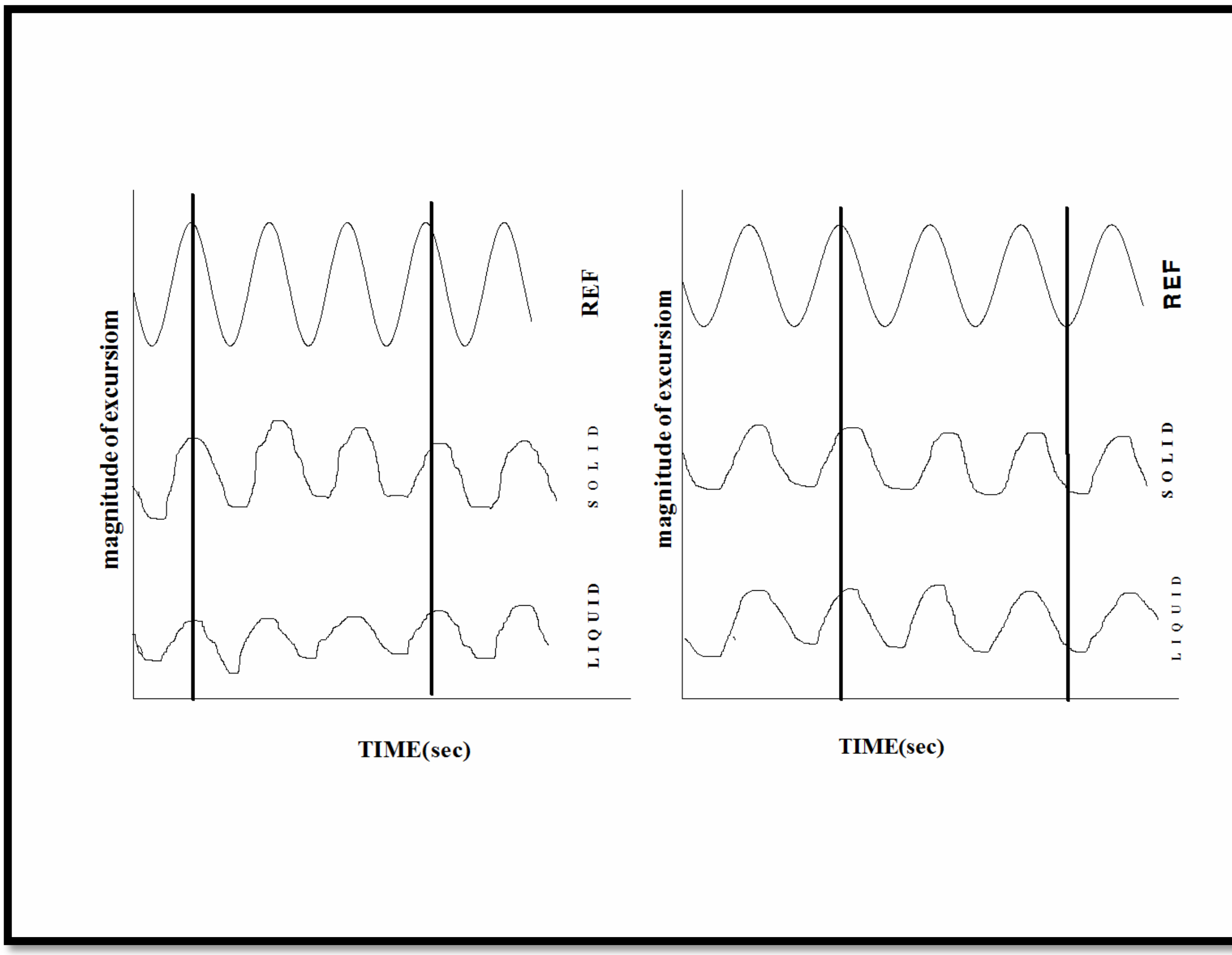


Figure14. Raw data figure of movement trajectory and finger-force profiles in Random task

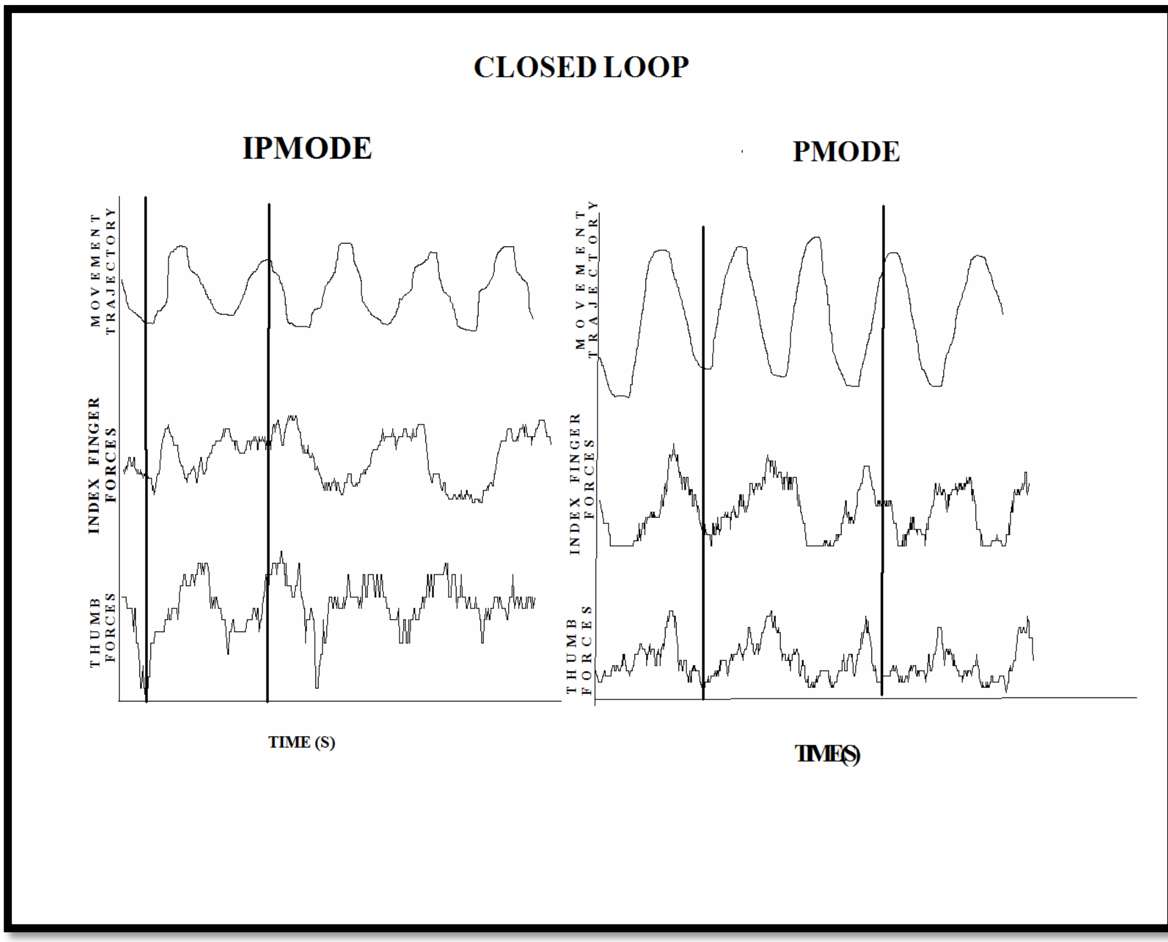


Figure15. Effect of mode of manipulation on MCC

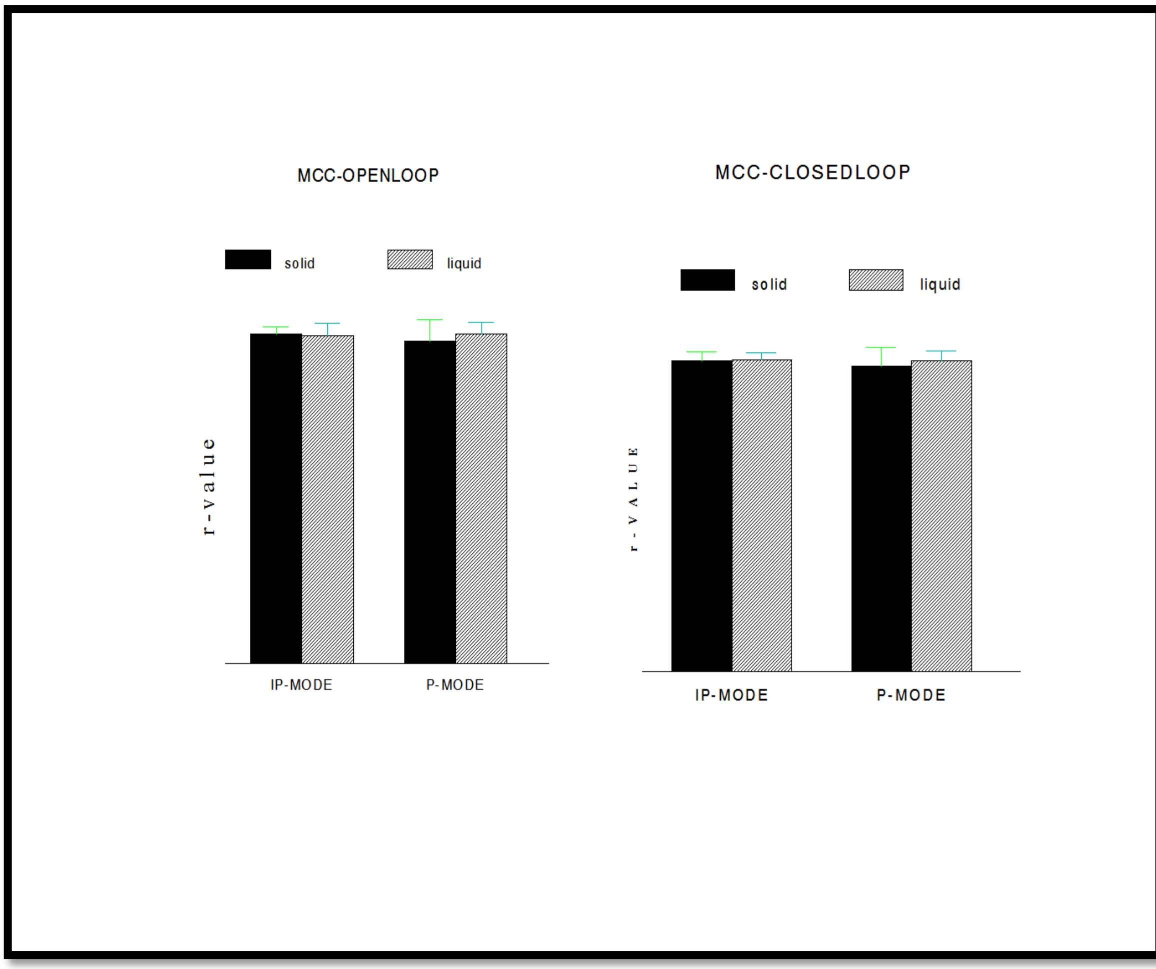


Figure16: Effect of mode of manipulation on amplitude consistency

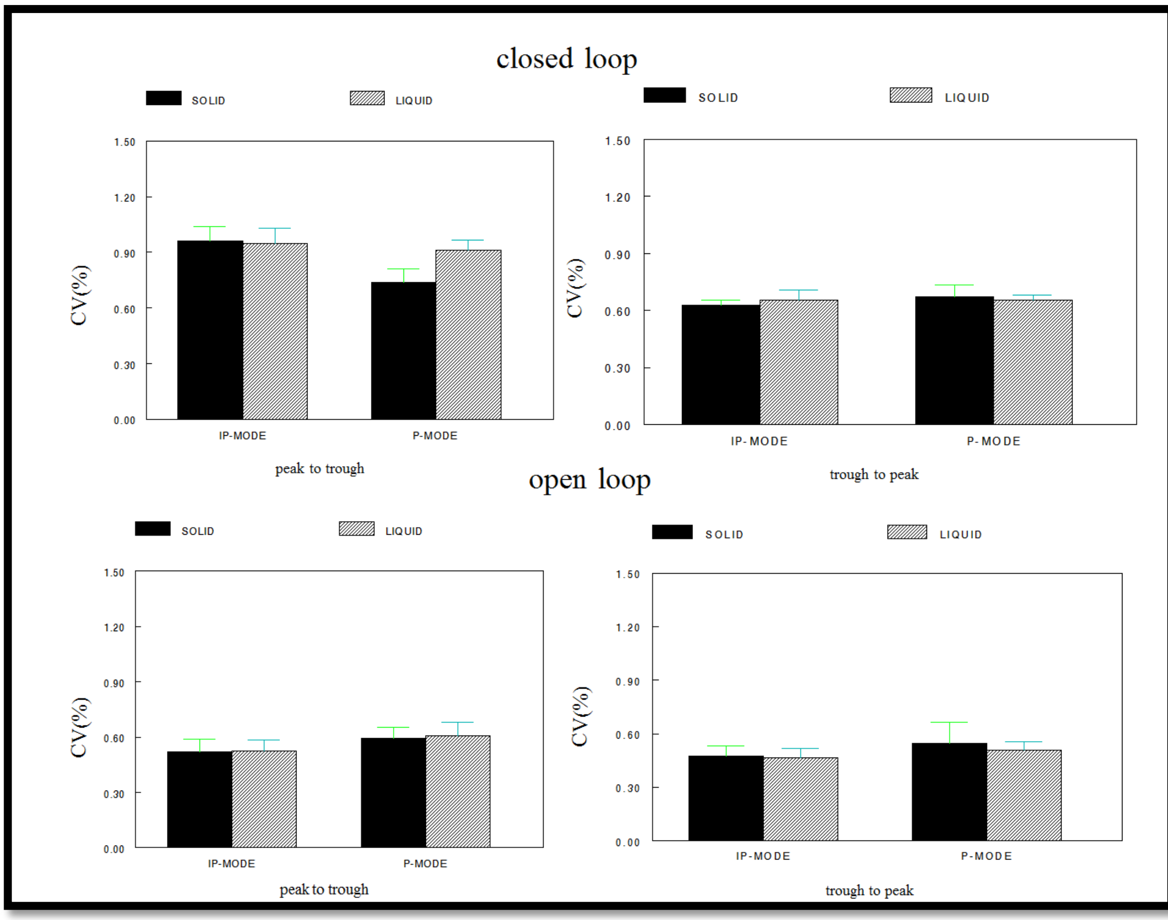


Figure17. Effect of mode of manipulation on temporal accuracy

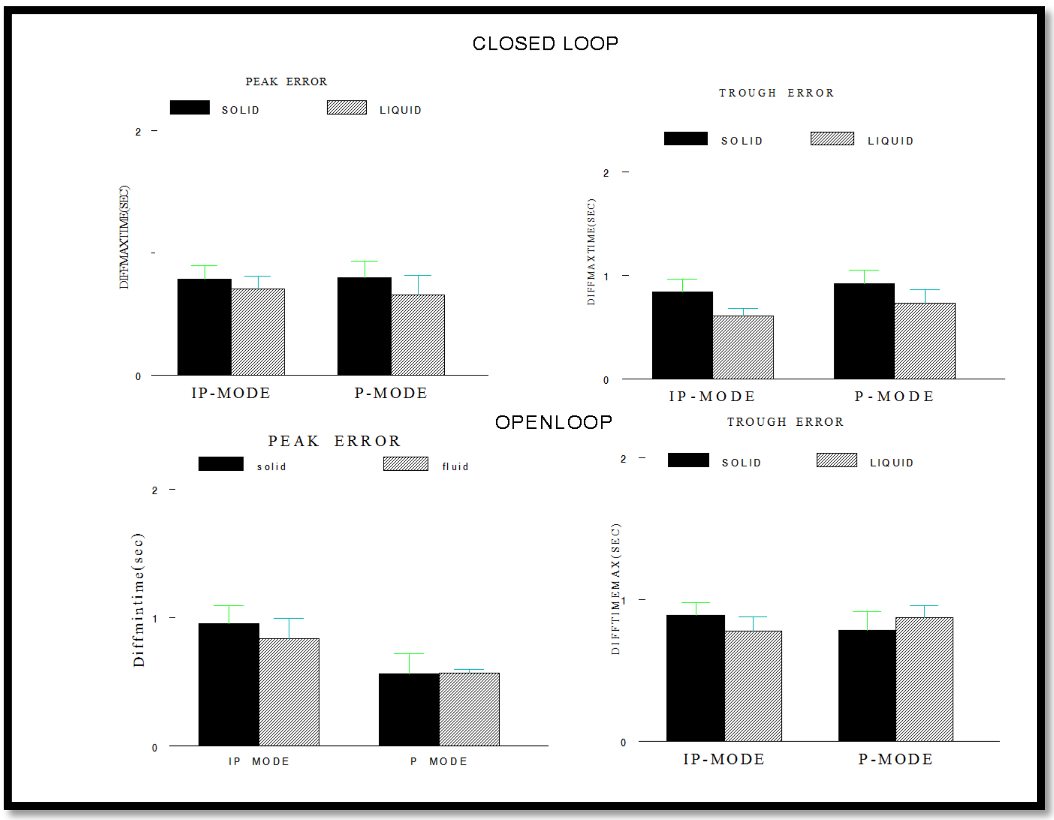


Figure18. RMS of thumb and index finger in IP-mode and P-mode

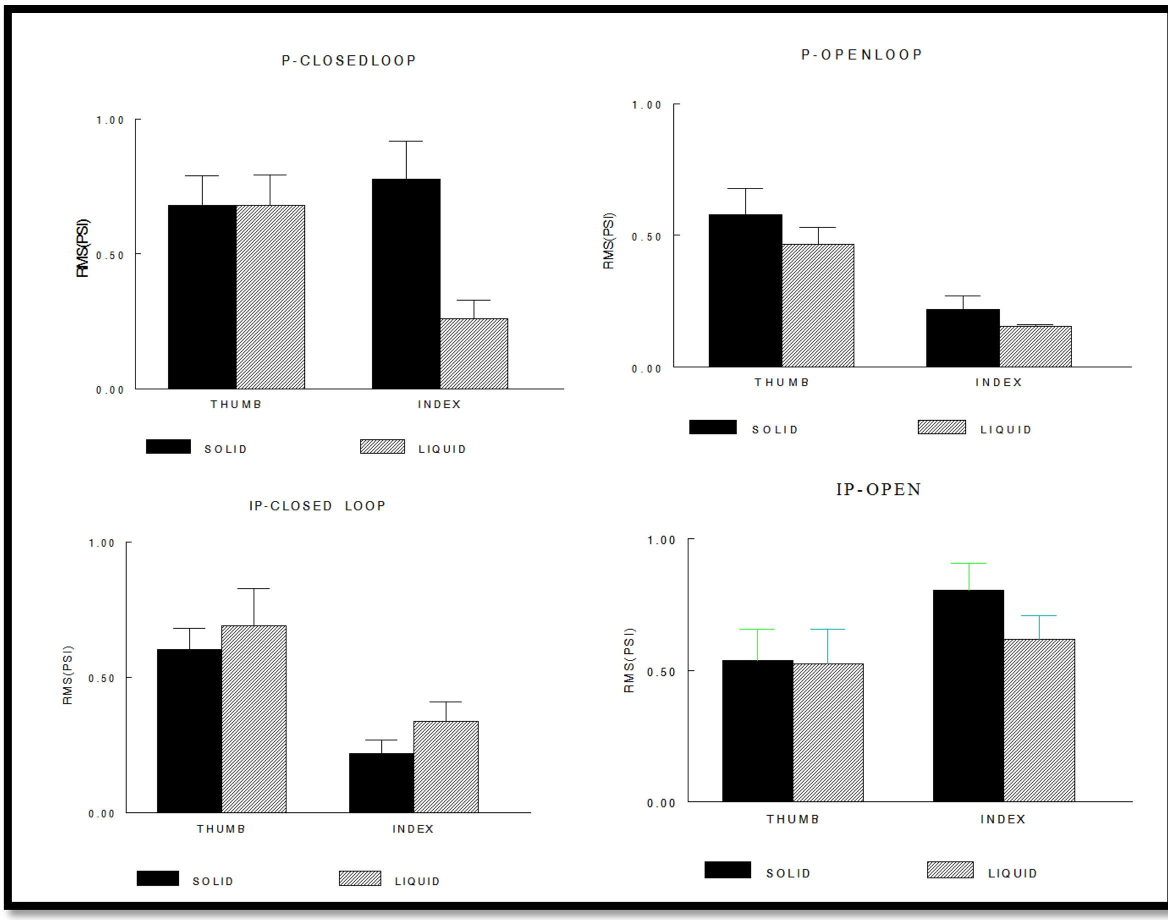


Figure19. Effect of mode of manipulation on score

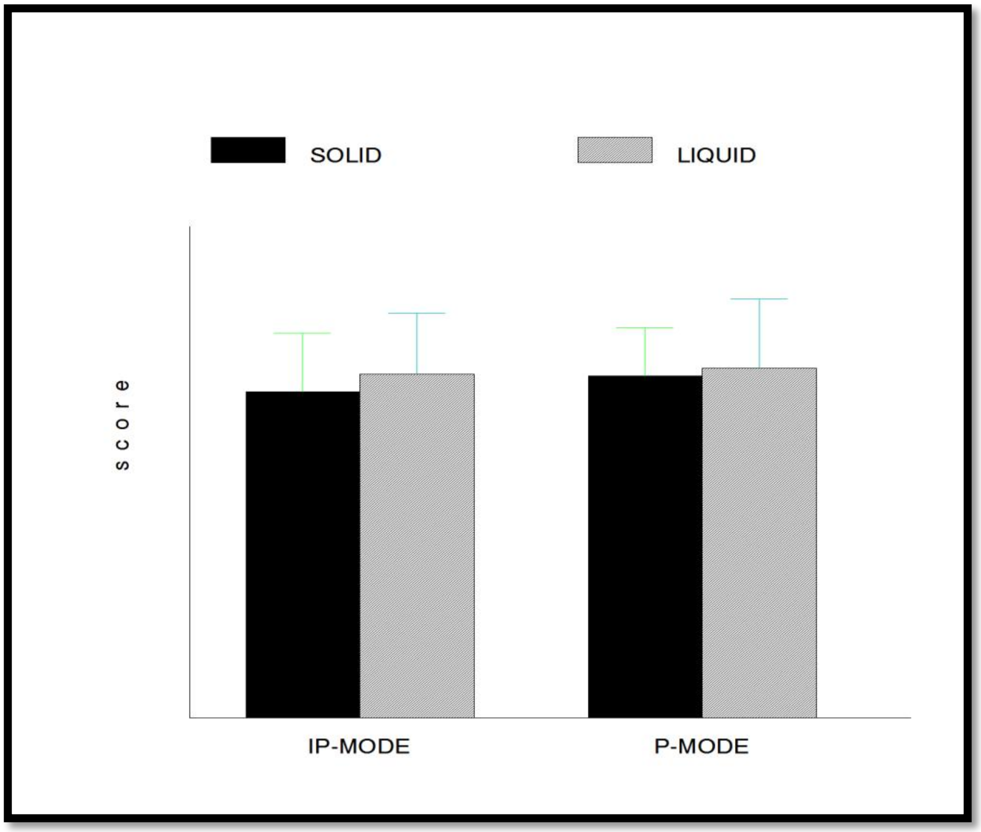
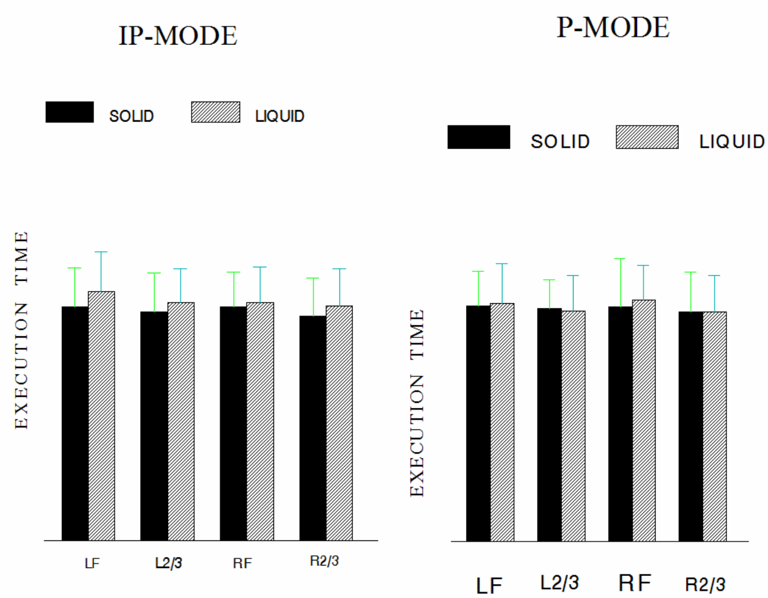


Figure20. Effect of mode of manipulation on movement execution time



LF-Left full upward movements

L2/3-Left upward 2/3movements

RF-Right full upward movements

R2/3-Right upward 2/3 movements

Figure21. Effect of modes of manipulation on motor initiation time

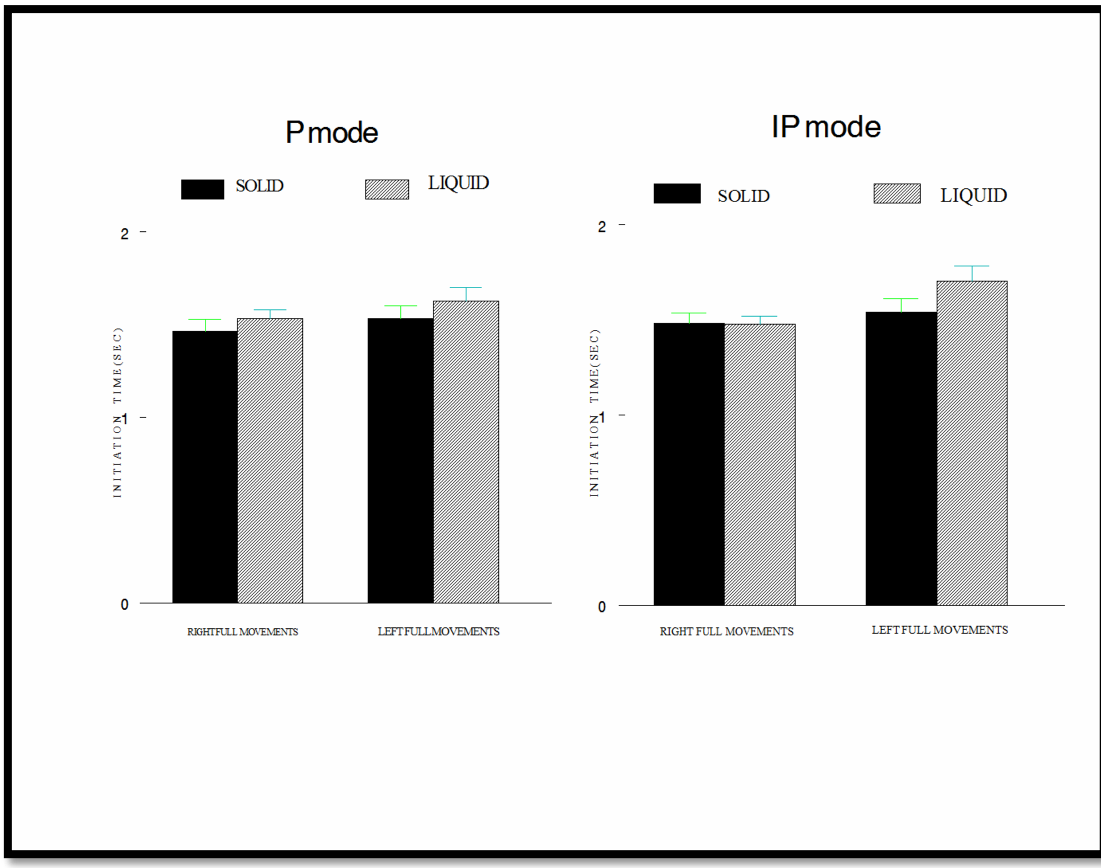


Figure22. RMS values of finger forces in random mode of assessment

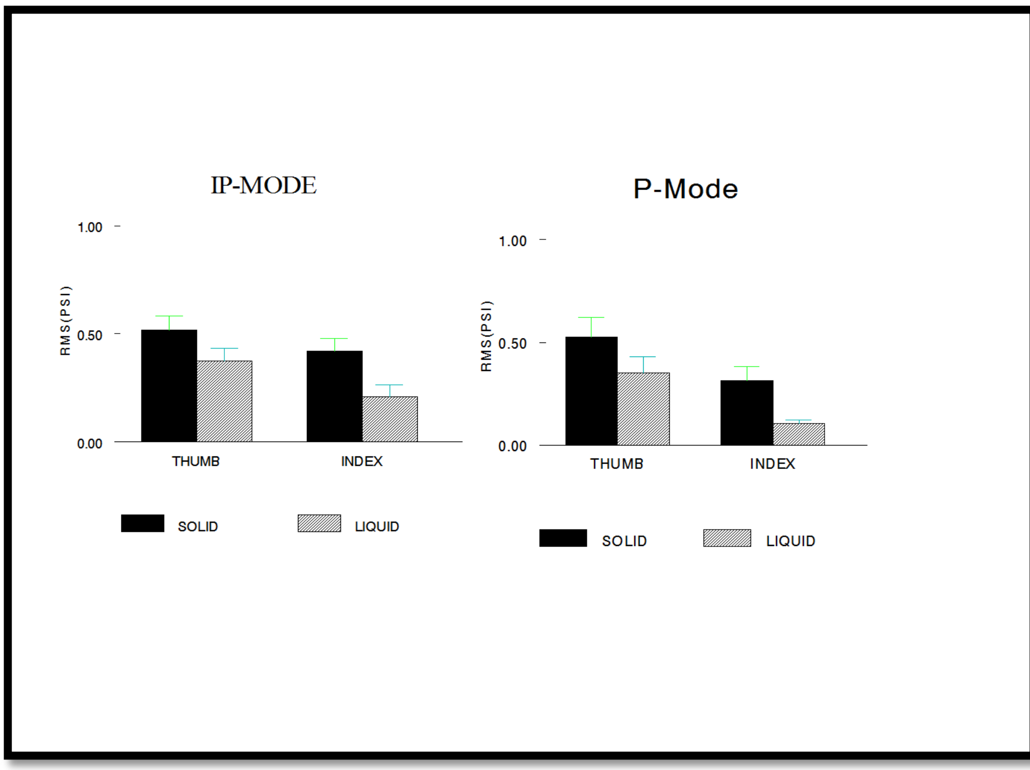


FIGURE LEGENDS

Figure1: Objects used in the study

Two coffee cups of 6.5 inches height were used in this study. A fluid filled cup (right) was filled with 325 ml of water to occupy ½ the space; the mass of the cup moved as it was tilted, and this produced an unpredictable moving COM location. A second cup, solid (left) was filled with the same quantity of water (325 ml), and a Styrofoam insert was placed on top to fill in the remaining space. This produced the same mass and COM location that remained fixed during the object tilt.

Figure2: Minibird™ (Motion tracker)

The Minibird Model 800 DC magnetic tracker (Ascension technology, Burlington, VT, USA) was attached to the objects for manipulation. This instrument is reliable and allows precise measurement of the 3-D spatial position and orientation of any object. The Minibird records up to 144 measurements per second, when the sensor is within ± 30 inches of the transmitter. 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, z follows the right hand rule. Orientation angles were defined as rotations about the X (roll), Y (elevation) and Z (Azimuth) axes of the sensor. Using the Minibird, we can instrument virtually any object and accurately record with precision, all forms of movement.

Figure3: Finger Force sensors

Individual miniature force sensors (FSA) Force Sensitive Applications Verg Inc. Winnipeg, Canada were used to measure the contact forces between the thumb and fingers digital pads and the object. The sensors were taped to the digital pads of thumb, index and middle fingers, using two-sided tape. These pressure sensors were configured to record a range of force from 50 – 150 mm Hg. The flexible peizo resistive sensors (1 cm square) are ultra thin and do not interfere with object manipulation, once the surface texture (co efficient of friction) is modestly adjusted. Pro wrap was used around the object to adjust the co-efficient of friction. The force sensors recorded contact forces during task performance.

Figure4: Experimental setup

Participants were made to sit comfortably in front of a computer monitor to perform the object manipulation tasks. Their arm was positioned approximately in 20 degrees shoulder flexion and neutral rotation, elbow in flexion, and the forearm in pronation and resting on a four-inch block of Styrofoam. A strap was used to eliminate any vertical motion. The wrist was flexed approximately 40 degrees, which also helped to prevent forearm or shoulder motion and contributed to the forward-backward motion of the cups. The participants were instructed to rotate the cups (towards and away from the body) in two modes of manipulation ie; P mode and IP mode in pace with the moving computer cursor. In addition to the cursor tasks participants were also instructed in playing a computer game.

Figure5: Modes of manipulation used

In general, a comparison of the reference cursor and respective object movements illustrates the ability to track the sinusoidal visual target in both P mode (left) and IP-mode (right). Forward tilting of the coffee cup required that participants hold the bottom of the cup in IP mode and the top of the cup in P mode between the thumb, long, and ring fingers and tilt the glass away from the body (maximum position) and then toward the body (minimum position). Maximum values in IP-mode reflect forward rotation of the top of cup, and maximum values in P-mode reflect forward rotation of the bottom of cup. Maximum excursion represents the peak and the minimum excursion represents valley

Figure 6: Open loop task

This task was guided by a moving cursor on a computer monitor. The participant was asked to rotate the cup in concert with the target cursor condition moving up and down at a fixed frequency and amplitude. A custom software program was created to move the on-screen cursor (large bright colored circle) in a predictable sinusoidal manner vertically (top to bottom on the display).

The thick arrow on left side of the figure illustrates tilting of the cup forward movement. The top arrow at the cup illustrates the position of the thumb and fingers on the cup being handled in P mode and the bottom arrow at the cup illustrates position of the thumb and fingers bottom of the cup illustrates IP mode.

Figure 7: closed loop task

In this task, two cursors of different colors appeared on the monitor. One is the target cursor as in the open-loop condition which was moving up and down. Motion of the second cursor (PADDLE) is slaved to rotation of the cup using a custom motion software program. The task goal was to overlap the two cursors during motion from the top to bottom edge of the monitor.

The thick arrow on left side of the figure illustrates tilting of the cup forward movement. The top arrow at the cup illustrates the position of the thumb and fingers on the cup being handled in P mode and the bottom arrow at the cup illustrates position of the thumb and fingers bottom of the cup illustrates IP mode.

Figure 8: Episodic task

A custom video game was used to generate episodic short duration precision movements of varying direction and amplitude. The goal of the test game is to move a paddle (game sprite) to catch objects (targets) moving horizontally left to right. The target objects appear every 2 seconds at random locations on the monitor from left to right.

The task complexity was Simple, involving a single target object to catch, which was a bright-coloured circle, moving horizontally from left side of the monitor to right. Each game lasted for 120 seconds. The arrow on left side of figure illustrates tilting of cup forward and back to neutral.

Hits on the left side of the screen tracks the number of targets caught and misses on right side of screen shows the number of targets missed during the game play. A score was calculated based on the number of hits and misses.

The thick arrow on left side of the figure illustrates tilting of the cup forward movement. The top arrow at the cup illustrates the position of the thumb and fingers on the cup being handled in P mode and the bottom arrow at the cup illustrates position of the thumb and fingers bottom of the cup illustrates IP mode.

Figure 9: Raw data from episodic task

Figure 9 (left panel) displays the raw motion coordinates of the computer game paddle sprite contained in one logged game data file. (Bottom Panel) Example plots of the parsed contextual game movements slaved to cup rotation of two healthy young adults, playing the game with one target only. Shown are medium-sized game play movements for one direction; magnitudes 1/3 to 2/3 of screen width.

The left panel of Figure1displays the raw motion coordinates of the computer game paddle sprite contained in one logged game data file. The y-axis is the magnitude of paddle motion (game controller); zero represents the left edge (or bottom) of the computer monitor, and maximum is the right edge (or top). The x-axis is time, representing the duration of the game session, in this case 120 seconds. This includes 60 game events, each 2 seconds in duration. The starting location of the target object is presented randomly relative to the paddle, and the distance varies from medium (one-third to two-thirds of the monitor distance) to large (two- thirds to full screen). The middle panel in Figure 2 show plots of the parsed “contextual game event windows” obtained from the raw coordinate and event logged data. Time zero is the onset of target appearance (onset of game event), and the end of event window is the time when the target reaches the other edge of the display, plus 500 ms to capture any overshoots of paddle movements. In the right panel, the parsed contextual event plots presented in the middle panel are sorted into “functional bins” representing movement direction and amplitude. In the right panel, only the parsed medium-sized movements are displayed. Individual parsed events are shown for leftward hand rotation (upward trajectories) and rightward hand rotations (downward trajectories). The top plots in each panel present records of game play where only one target object is used. The bottom plots are when using target plus 2 distracters objects.

Figure 10: Analysis of temporal accuracy and amplitude consistency

The figure shows a representative waveform comparing the trajectory of performance (thin line) for one of the tasks to the target cursor trajectory of the reference sinusoidal waveform (thick line). Along the y-axis is the relative amplitude excursion and time in milliseconds is on the X-axis.

A. Vertical lines illustrate the time difference in reaching the maximum (peaks) and minimum (valleys) trajectories. The dotted line shows the maximum excursion for the performance compared to maximum excursion for the reference sinusoidal waveform (dark line).

B. The bottom portion of the figure illustrates a representative waveform and the calculation performed to obtain the excursion of motion. The maximum amplitude (peak) subtracted by the minimum amplitude (valley) as indicated by the arrow outlines the relative excursion for one cycle.

Figure11: Analysis of episodic task variables

This figure shows how the participant performance during game play was quantified. The y-axis represents the screen width i.e.; is the magnitude of paddle motion (game controller); zero represents the left edge (or bottom) of the computer monitor, and maximum is the right edge (or top). The x-axis is time, representing the duration of the game session, in this case 120 seconds. This includes 60 game events; each 2 seconds in duration .These are “functional bins” representing movement direction and amplitude, only the parsed medium-sized movements (upward trajectories) are displayed.

The small dotted line represents the time from the appearance of the target to start of the paddle movement; this output variable is gathered by looking at the velocity curve for each of the user movement trajectories. The maximum point of the velocity curve was considered the beginning of the movement. The sample value was then converted to a time in milliseconds based on the sampling frequency. It is calculated by subtracting the maximum velocity sample from the event start time. These times are averaged together to give a more accurate picture of the overall response time or movement initiation time of the player.

The big dotted line represents the average movement execution time or total movement duration. It is calculated as 90% of the time between movement initiation and final paddle position. We consider only 90% of the time because there is a latency period of 10% between target appeared and person hitting the target. This event is triggered as soon as a target enters the screen. From that point, the user movement is timed, and then they either reach the target and destroy it or missed it.

The stars' in the figure showing hits and misses represents how many targets were caught and how many of them were missed during the game play. Based on these results the score was calculated.

Figure12: Raw data figure of movement trajectory and finger-force profiles in open-loop task

Raw data figure of open-loop tasks. Typical plots of reference target cursor and cup movement trajectories for IP-mode (Top panel) and P-mode (Bottom panel) of one representative subject in open-loop mode.

In general, a comparison of the reference cursor and respective object trajectories illustrates the ability to track the sinusoidal visual target in both IP-mode and P-mode.

Vertical lines illustrate the maximum excursion (peak) between the first and second cycles and the minimum excursion (valley) between the second and third cycles. Maximum values in IP-mode reflect forward rotation of the top of cup, and maximum values in P-mode reflect forward rotation of the bottom of cup.

In this figure the actual object trajectories during both P- and IP-mode there were no differences noticed in open-loop mode for both solid and liquid. In open-loop mode, the movement profiles exhibited regular cyclic pattern in both P- and IP-mode while manipulating solid and liquid cups. For the most part, actual trajectories exhibited consistent, regular sinusoidal patterns similar to the reference trajectory. Maxima and minima at the turning points were seen for each half cycle, and the phase (timing of maxima and minima, vertical lines) were similar.

Figure13. Raw data figure of movement trajectory and finger-force profiles in Closed-loop task

Figure 13 shows the raw data figure of closed-loop tasks. Typical plots of reference target cursor and cup movement trajectories for IP-mode (left panel) and P-mode (right panel) of one representative subject in closed loop mode.

In general, a comparison of the reference cursor and respective object trajectories illustrates the ability to track the sinusoidal visual target in both IP-mode and P-mode. Vertical lines illustrate the maximum excursion (peak) between the first and second cycles and the minimum excursion (valley) between the second and third cycles. Maximum values in IP-mode reflect forward rotation of the top of cup, and maximum values in P-mode reflect forward rotation of the bottom of cup.

In closed-loop mode, the movement profiles exhibited an irregular cyclic pattern in IP-mode while manipulating solid and liquid cups but showed a clear cyclic pattern for both cups in P-mode. Also, plateau periods were more evident at the maximum backward position of the object in the pendulum mode closed-loop mode.

Figure14. Raw data figure of movement trajectory and finger-force profiles in Random task

Figure 14 shows raw data figure of movement trajectory and finger-force profiles in closed-loop tasks. The plots of movement trajectory and finger-force profiles of a single subject in both modes of manipulation in closed-loop mode. The left panel shows P-mode, and the right panel shows IP-mode.

Distinct movement-related cycles of plateau and “off” period were clearly evident in all digits-force profiles in both modes of manipulation. In the inverted pendulum mode, at the maximum forward position of the cup, the thumb forces peaked opposite to index finger forces, i.e., in the inverted pendulum mode, during the forward rotation of the cup, the thumb-force profiles increased, indicating that most of the load was transferred onto the thumb compared to the index finger. In the pendulum mode, at the forward position of the object, i.e., when the bottom of cup was tilted, both the thumb force and index finger forces peaked after the object maximum. (See panel left and right, Figure 14).

Figure15. Effect of mode of manipulation on MCC

Figure 15 shows the Effect of mode of manipulation on MCC.It Presents group means and standard error of means (SEM) of maximum cross-correlation coefficient (MCC) between target cursor and actual movement trajectory, closed loop on left and open loop on right. There was statistically no significant effect of mode of manipulation on MCC.

Figure16. Effect of mode of manipulation on amplitude consistency

Figure16 presents group means (SEM) of amplitude consistency calculated by coefficient of variation. Top panel shows closed loop mode and bottom panel shows open-loop mode. There was no significant effect of fluid motion (solid vs. fluid) on amplitude (COV) in both open- and closed-loop mode. There was also no statistically significant effect of mode of manipulation on amplitude (COV) in open-loop mode. However, significant differences were found with the closed-loop task .Mode of manipulation (IP versus P) also had a significant effect on amplitude consistency min to max.

Figure17. Effect of mode of manipulation on temporal accuracy

Figure17 presents Group means (SEM) of temporal accuracy. Top panel shows closed loop mode and bottom panel shows open loop mode. There was no significant effect of fluid motion (solid vs. fluid) or mode of manipulation (IP versus P) in open-loop mode. However, in closed-loop, mode of manipulation (IP versus P) had a significant effect on temporal error maximum .Mode of manipulation (IP versus P) also had a significant effect on temporal error minimum in closed-loop mode.

The quality of movement was better in pendulum mode than inverted pendulum movement.

Figure18. RMS of thumb and index finger in IP-mode and P-mode

Figure18. Group means (SEM) of RMS thumb and index finger. IP-mode on left and P-mode on right. Top panel shows closed-loop mode and bottom panel shows open-loop mode. In both open-loop and closed-loop mode, there was no significant effect of either fluid motion (solid vs. fluid) or mode of manipulation (IP versus P) on RMS of the finger contact forces.

Figure19. Effect of mode of manipulation on score

Figure 19 presents the effect of mode of manipulation on score.There was no statistical effect of mode of manipulation on score. There was no statistically significant effect of mode of manipulation (IP vs. P) on score.

Figure20. Effect of mode of manipulation on movement execution time

Figure 20 presents the effect of mode of manipulation on movement execution time. Presents group means (SEM) of motor execution time. Left panel for P-mode and right panel for IP-mode. There was no statistically significant effect of mode of manipulation (IP vs. P) on movement execution time.

Figure21. Effect of modes of manipulation on motor initiation time

Figure 21 presents Effect of mode of manipulation on motor initiation time. Presents group mean (SEM) of motor initiation time. Left panel for P-mode and right panel for IP-mode. There was no statistically significant effect of mode of manipulation (IP vs. P) on motor initiation time.

Figure22. RMS values of finger forces in random mode of assessment

Figure 22 presents group means (SEM) for RMS values of finger forces in episodic movement tasks. There was a statistically significant effect of fluid motion (solid vs. fluid) on RMS of thumb. There was also a statistically significant effect of fluid motion (solid vs. fluid) on RMS of index finger contact forces. There was no statistically significant effect of mode of manipulation (IP vs. P) on RMS of thumb and index finger.

Table 1

Statistical Table showing the Effects of Fluid Motion (Fluid vs. Solid) and Mode of Manipulation (IP vs. P) on the Dependent Variables in Predictable (Closed-loop) Mode of Assessment. This table Summarizes results of the repeated measures ANOVA.

Closed loop (predictable mode of assessment)			
	FACTOR A (FLUID VS. SOLID)	**FACTOR B (MODE OF MANIPULATION)**	**INTERACTION EFFECTS (FACTOR A*FACTOR B)**
Temporal error max	N.S.	**P<0.050 F=6.167**	N.S.
Temporal error min	N.S.	**P<0.050 F=5.346**	N.S.
Amplitude consistency (max to min)	N.S.	**P<0.001 F=13.517**	N.S.
Amplitude consistency (min to max)	N.S.	**P<0.001 F=13.089**	N.S.

Amplitude consistency (max to min) using COV)	N.S.	N.S.	N.S.
Amplitude consistency (min to max) using COV)	N.S.	**P<0.050 F=4.226**	N.S.
RMS-thumb	N.S.	N.S.	N.S.
RMS-index	N.S.	N.S.	N.S.
MCC	N.S.	N.S.	N.S.

Table 2

Statistical Table showing the effects of Solid vs. Fluid and Mode of Manipulation IP vs. P on the Dependant Variables in Episodic Mode of Assessment. This table Summarizes results of the repeated measures ANOVA. Post-hoc comparisons were done using Tukey's test, $p < 0.05$.

Playing a video game (Episodic movement task)			
	FACTOR A (FLUID VS. SOLID)	**FACTOR B (MODEOF MANIPULATION)**	**INTERACTION EFFECTS (FACTOR A*FACTOR B)**
Success %	N.S.	N.S.	N.S.
Average response time	N.S.	N.S.	N.S.
Average residual error	N.S.	N.S.	N.S.
Movement execution time	N.S.	N.S.	N.S.
Absolute movement error	N.S.	N.S.	N.S

RMS-thumb	**P=0.038** **(p<0.05)** **F=4.473**	N.S.	N.S.
RMS-index	**P=0.005** **(p<0.01)** **F=8.820**	N.S.	N.S.