MOTOR CONTROL IN COMPOUND MOVEMENTS INVOLVING PREHENSION

by

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B.Sc., UNLV, 1995

M.Sc., UNLV, 1997

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
in the school
of
Kinesiology

SIMON FRASER UNIVERSITY
June 2002

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TITLE OF THESIS: Motor Control in Compound Movements Involving Prehension

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Title of Thesis/Project/Extended Essay

Motor Control in Compound Movements Involving Prehension.

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ABSTRACT

A series of three experiments was designed to investigate the control processes involved in multisegmental coordination. Each of the experiments required subjects to perform a prehension task either: a) with the assistance of torso flexion, or b) while walking. In Experiment 1, we had subjects grasp, transport, and set down a cup of water while walking past a table. The results of Experiment 1 suggested subjects adjusted their gait patterns both at the time of cup lift and cup replacement. Furthermore, when the task was made more complex by removing the lid from the cup, the gait adaptations became more pronounced. For Experiment 2, subjects were seated and required to reach for and grasp a cup of water that was placed beyond the reach of the extended arm. The results of this experiment revealed the evolution of an interesting relationship between the arm and the torso. Individually, both the arm and the torso demonstrated a kinematic precision effect, or a lengthened deceleration phase, when reaching for full versus empty cups. Within-subject variability results showed that the displacement of the endpoint (arm + torso) took precedent over the torso or the arm alone. Therefore, it would seem that the motion of endpoint through space was carefully planned and monitored. Experiment 3 brought together elements of each of the previous two experiments. As in Experiment 1, subjects were asked to grasp and transport cups of water while walking. The results of Experiment 3 indicated that increasing the complexity of the task (i.e., adding water to the cup) impacted the movement profiles of the upper limb, the torso, and the gait system. Regarding the upper limb, it was shown that the wrist reached greater peak velocities when reaching to grasp an empty or a half-full cup as compared to when the cup was full. Furthermore, the torso was found to play a greater role in terms of its

forward displacement and its angular rotation when the cup was full. The locomotion system was similarly affected in that a greater amount of time was spent in stance phase when subjects picked up cups that were full versus those that were half-full or empty. Interestingly however, the magnitude of the within-subject endpoint variability was not affected by the level of water in the cup, suggesting that a system of motor equivalence was at work to maintain a consistent end effector position. Further results indicated that indeed, the within-subject variability of the endpoint decreased to a greater extent than did the torso or the arm alone. The combined results of the aforementioned experiments demonstrated that individual movement segments were readily able to utilize a single, functional neuromuscular synergy to meet the demands of a given task.

ACKNOWLEDGEMENTS

My sincerest thanks go out to my advisor and mentor Dr. Ronald G. Marteniuk for the time and resources he invested in me over the four or so years this work took to complete. The difficult and oftentimes tedious endeavor of writing a Ph.D. dissertation was eased greatly through his patience, friendship, generosity, and keen insight into the relevance of this work.

I would like to acknowledge my parents David and Robin Harron. Simply put, I could not have completed this degree without their infinite love and support through the many trying times that accompanied the years spent dedicated to this project. Thanks seem like a trivial gesture when I consider all these two people have done for me, but I am, nonetheless, thankful.

And finally, I would to acknowledge Ms. Kelly Ann Margaret Pretty. Kelly came into my life as I was nearing the end of this dissertation, but her role in its completion was as significant as any. Thank you, Ms. Pretty, for giving me the strength to push through to the end, and for inspiring me to yet greater heights.

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Chapter 1: Introduction

1.1 Motivations

Motor control research has traditionally followed a reductionist philosophy. In other words, the way in which the majority of researchers have set about the task of understanding movement principals has been to constrain movements into more easily observable forms, with the underlying premise being that a complex system can be understood in terms of its isolated parts. This approach has proven to be a fruitful one in most, if not all areas of human movement science. In prehension research for example, it has led to the understanding that prehensile movements are comprised of separate, yet temporally coupled, components: the transport and the grasp (Jeannerod, 1981, 1984).

Technologies such as electromyography and 3-dimensional motion analysis have bolstered the reductionist approach by allowing scientists to dissect even the simplest movements into their component parts. It is now possible, for example, to track a ballistic movement at 10,000 Hz, a feat that would have seemed otherworldly just 30 years ago. It is somewhat ironic that these same technologies, designed to help scientists study the microstructure of movement, are now making it possible to observe motor behavior in much broader contexts. As a result, researchers have been provided with the unique opportunity of studying human coordination in much more elaborate ways.

Coordination is a term that is widely used both in scientific literature, and in everyday conversation. In sporting terms, a coordinated individual is one who can hit a baseball thrown at them at 90 miles per hour, or a gymnast who can perform acrobatics on a narrow balance beam. There is no question that these athletic endeavors are extraordinary feats of coordination; however, in actuality even the most mundane of human actions require a tremendous amount of coordination. Walking for example, an activity that most would consider to be one of the most basic human movements, requires the highly developed interplay of numerous muscle groups and countless neurological pathways. In terms of skilled movement then, coordination can be thought of as the bringing together of various movement components in an efficient and harmonious fashion.

Scientists have studied movement of the human body since the 1800's, when such prominent figures as Sherrington and Woodworth first began recording and measuring voluntary action. In the time since those early efforts, a tremendous amount has been learned about human motor behaviour and the neurological processes that underlie it. Specifically with regard to research involving the upper limbs, the past 20 years has seen an explosion of interest in the areas of pointing, aiming, and prehension. Many of these experimental paradigms adopted to study the hand have employed movement-limiting devices such as chest straps (e.g., Gentilucci, Chieffi, Scarpa, & Castiello, 1992), or headrests (e.g., Jeannerod, 1984) in an attempt to reduce upper limb activity to a movement involving only the hand and arm. Although such approaches have been beneficial, it is nonetheless important to realize that in natural settings, the hand seldom, if ever, moves in isolation from the rest of the body. One might ask whether the results (and the inferred underlying control processes) obtained from these "controlled" situations can be generalized to movement as it occurs in our everyday activities where reaching and grasping are often combined with movements of other body parts. Ideally then, it could be suggested that a more meaningful way to observe human movement would be to allow the body and its many degrees of freedom to move naturally in experimental settings. Of course, the downside to such an approach is that it is often a troublesome and impractical matter to measure more natural movements in a precise way.

Recently in our lab, we have designed a series of experiments with the dual purpose of minimizing unnatural movement constraints and quantifying the relationships between movement segments in a meaningful way. Underlying much of this work are two issues, one theoretical and the other methodological. The theoretical issue deals with the notion of motor equivalence, which has been described as variable means to invariant ends (Abbs & Cole, 1987; Bernstein, 1967; Lashley, 1930). One way to identify motor equivalence is to observe relatively variable component submovements that lead to relatively invariant overall movement performance. Our view is that the prehension studies that have artificially restricted the movement of other body parts during the prehension act may have missed the contribution from these additional degrees of freedom. We suspect that asking how these other degrees of freedom enter into the coordination of prehension acts may enrich our understanding of how prehension is controlled. Methodologically then, our aim has been to first design experiments that permit motor behaviours to be expressed more naturally, and secondly to quantify the movements of the involved segments both individually and relative to one another. Finally, our aim is to place the results of these experiments into a larger theoretical framework that more fully explains and expands upon current notions of human coordination.

1.1.1 Quantifying Coordination

In motor control research, the issue of coordination has been investigated on several fronts. Specifically, the control of eye, head, and hand movements during prehensile tasks has garnered significant attention in current literature (e.g., Carnahan, Roy, & Elliott, 1993) as have studies looking at the roles of various speech articulators in sound production (e.g., Abbs and Gracco, 1984). An important first step in understanding coordination is quantifying the absolute movement of the involved body segments. In a trunk-assisted reaching experiment, Steenbergen, Marteniuk, and Kalbfleisch (1995) measured the movement of both the grasping hand as well as the motion of the body. We have come to realize now that additional, perhaps more important, information can be gained from observing how the individual segments move in relation to one another. Toward that end, a certain methodological framework underlies much of the work that is to be outlined in this dissertation. We hope to ascertain if, during a prehension task, the hand exhibits relatively invariant spatial trajectories and if the other degrees of freedom related to torso and leg movements vary in their contributions in order to preserve the consistent end-point trajectories of the hand. To accomplish this, we have employed two methods for determining the movement of the hand during a prehension task. Using an OPTOTRAK (Northern Digital, Waterloo, Ontario) 3-dimensional motion analysis system and two frames of reference to analyze the resulting kinematics: 1) a traditional. world-centered frame of reference; and, 2) a chest-centered frame of reference (Bertram, Mason, Mackey, MacKenzie, & Marteniuk, 2000). The first method is one used by most studies on prehension where hand movement has been quantified by describing the movement in X, Y, and Z coordinates relative to the workspace of the task (also called world- or room-centered coordinates). Here, the origin of each of the axes is usually arbitrarily assigned to some location on the table upon which the objects to be grasped are placed. The other view of the hand, which we call body-centered, uses the torso as a dynamic frame of reference. In this case, an infrared emitting diode (IRED) is placed on the torso and the three-dimensional difference between this IRED and the IRED of the hand is recorded for each frame of movement. Another way to describe these plots is to consider that the data represented in the world-centered plots is the combined action of the torso and the arm. In essence then, these data reflect the synergistic effort of the motor control system to transport the endpoint (i.e., the wrist IRED) through space using degrees of freedom from both the trunk and the upper limb. The body-centered plots then, which are obtained by calculating the distance between the wrist and trunk at every sample point, reflect the movement profile of the arm alone, independent of any torso movement.

The experiments in this dissertation concern tasks that involve compound movements of the upper limbs, torso, and lower limbs. By observing the motion of these three segments individually and in relation to one another, we hope to gain an understanding of how coordinated action develops and unfolds under various experimental conditions. In particular, we hope to demonstrate how the multiple movement segments, each with their own degrees of freedom, are able to work together in a task-specific manner to achieve a movement goal. A common theme that will be developed throughout this dissertation is that of motor equivalence – or how variable means can be employed to produce invariant ends in multisegmental movements. Furthermore, we will investigate how the phenomenon of motor equivalence appears to emerge in response to increases in task complexity.

1.2 Overview of Experiments

Three experiments have been designed to investigate the planning and control of coordination in compound movements involving prehension. An experimental manipulation common to all three experiments was that the object to be grasped (and in some cases transported) was a small plastic cup. In Experiment 1, the cup was filled with water. For half the trials, the cup was uncovered and therefore prone to spilling. For the remainder of the trials however, the cup was covered and therefore resistant to spilling. For Experiments 2 and 3, the cup was uncovered in all cases, however the level of water in the cup was manipulated. Trials in these experiments involved three blocks of trials: 1) an empty cup, 2) a half full cup of water, or 3) a full cup of water. The underlying premise behind these manipulations was that the planning and control involved in reaching for (or transporting) uncovered or more filled cups of water is more complex than are movements involving covered or less filled cups. It is important to note however, that the inherent *complexity* in these tasks involves more than the mere "spillability" of the cup. As one would expect, a full cup of water weighs more than an empty cup, all other things being equal, and no attempt was made here to make the situation appear otherwise. Although the weight of an object has not been found to affect the reaching component of prehension (Weir et al., 1991), it was nevertheless *not* the aim of this experiment to describe the differential effects of object properties on the motor control system. Rather, our goal was to design experimental conditions that differed enough in terms of their difficulty (i.e., complexity) so as to challenge the system. Whether that challenge was brought about by the level of fluid in the cup, the weight of the cup, or some other variable was not at issue in the present experiments. In summary, although the term *complexity* will be used throughout this dissertation to refer to increases in the likelihood of spilling a cup of water, it is acknowledged that spillability is at best only one aspect of what could potentially make a task complex.

The two types of compound movements of interest in this dissertation are: 1) tasks that involve the combination of prehension and locomotion, and 2) tasks involving trunk-assisted prehension. These two forms of movement, though fundamentally different, share the common element of body segments working in cooperation in order to successfully carry out the task. In addition, the case is made that these two types of experiments are also related theoretically, such that a common feedback/feedforward mechanism could potentially underlie the coordination observed in compound movements of this nature. The three proposed experiments are as follows:

Experiment 1: Does adding complexity to an upper limb task result in gait adaptations?

Experiment 2: The effects of incremental increases in task complexity on trunk-assisted prehension.

Experiment 3: The effects of incremental increases in task complexity: A further investigation into multi-segmental coordination in a prehension task involving locomotion.

Experiment 1 was designed to determine if adding complexity to a prehension task would result in adaptations beyond the upper limb. As will be discussed in subsequent sections of this paper, research on this topic has proven inconclusive. The preliminary results of this study suggest that indeed, if the conditions of a prehension task differ significantly in terms of their complexity, adjustments are seen not only at the level of the hand, but in various phases of locomotion as well. Experiment 1 provides evidence that under certain circumstances, different segments of the body will work in a coordinated manner in order to bring about successful task completion. Gaining insight into the nature of this multi-segmental cooperation was a primary motivation for Experiments 2 and 3.

For Experiment 2, we turned to a trunk-assisted reaching task. The goal of Experiment 2 was to examine the relationship between the arm and torso in a prehension task that requires the forward movement of the torso to allow the hand to reach its target. Previous work in our lab had found that when the hand was reaching for an uncovered cup of water, the torso played a more significant role in the movement than when the cup was covered (Mackey, Bertram, Mason, Marteniuk, & MacKenzie, 2000). In Experiment 2, we manipulated task complexity by having subjects reach for and grasp cups that were empty, half-full or full of water. Having three levels of complexity allowed us to investigate if the aforementioned adjustments in the hand and torso were progressive in nature, or whether they were more of an all-or-none phenomenon. Furthermore, qualitative analyses suggested that when the hand was reaching for an uncovered cup, the trajectories of the endpoint were less variable. A second goal for Experiment 2 was to quantify this variability to determine if the apparent differences that we have previously observed can be verified statistically.

Experiment 3 followed a similar paradigm to Experiment 2 in that again, cups that were empty, half-full or completely full defined the three levels of task complexity. In Experiment 3 however, subjects were walking when they picked up the cups as opposed to being seated at a table. In this case, we again attempted to determine if incrementally adding task complexity to the prehension task will lead to progressive adjustments in the participants' hand and/or gait patterns. Finally, as was the case with Experiment 2, we were interested in quantifying the spatial variability that occurs from trial-to-trial to help further explain how the arm and the body work together to achieve task goals.

Chapter 2: Review of Related Motor Control Literature

Before discussing the issues specifically related to compound movements, it is first imperative that one have a thorough understanding of the separate (though possibly related) entities of locomotion and prehension, and how the torso links the two together. Each of these movement systems will now be discussed in turn.

2.1 Research Relating to Human Locomotion

In the simplest possible terms, locomotion is the act of moving one's self from one place to another. From an infant crawling, to a monkey swinging through a tree, the ability to change position in space and time is a common link throughout the animal kingdom. Gait, on the other hand, refers to a particular style of moving on foot and can include such actions as walking and running. For the purposes of the present paper, the discussion that follows will be concerned with aspects of locomotion that relate to human ambulation, or walking.

In humans, walking is essentially the action of alternately advancing each foot in order to move from one location to another. A good place to begin an examination of human gait is to discuss some of the naturally occurring regularities seen in normal walking. Rosenbaum (1991) discusses three such regularities. The first is that the swing phase of walking, or the time the leg spends in the air between successive footfalls, hardly changes with walking speed. However the stance phase, or the time that each foot remains on the ground, will decrease as walking speed increases and vice versa. The third regularity commonly observed in gait analysis is in regard to the time-varying angles of the lower limb. More specifically, it has been well established that during locomotion the angular changes of the knee and hip are systematic in nature (e.g., Enoka, 1988). Any abnormalities in these patterns can serve as indications of injury or disease.

Locomotion operates in many instances as a means for achieving a goal (i.e., crossing a room or running to catch a ball). Our ability to accomplish such tasks is dependent upon the complex interplay between hard-wired motor programs, on-going feedback processes and possibly corrective feedforward mechanisms. Using the fictive locomotion procedure, Grillner (1981) was one of the first researchers to investigate this interplay in a carefully controlled setting. By functionally isolating the spinal cord from the brain, Grillner was able to show that the spinal cord, without input from the brain and without peripheral input from the muscles, was still able to produce rhythmic bursts of activity. This study confirmed earlier suppositions that a central pattern generator regulates walking. Grillner and his colleagues later showed that in addition to producing basic locomotor rhythms, the spinal cord is also able to produce more detailed electrical patterns in which different legs receive different neural signals. The presence of central pattern generators should not, however, underscore the role of the brain in locomotion. For example, before any purposeful movement can occur in the lower limbs, we must first *decide* upon an appropriate course of action (i.e., speed, path, etc.). Likewise, although it has been shown that the act of walking can and does occur without the benefit of peripheral feedback, it is nonetheless apparent that feedback is imperative for effective walking in any functional sense.

The visual system in particular plays an important role in the maintenance of locomotion. Obstacles and uneven terrain are common examples of potential hazards to walking that go virtually unnoticed in most situations due, in large part, to visual feedback. Georgeopolis and Grillner (1989) showed a marked increase in the corticospinal tract activity of cats when they walked over uneven (versus flat) surfaces. Vision also plays a significant role in the development of coordination. An experiment by Held (1965) explored the issue the development of visuomotor coordination by observing how the visual and motor systems interact in kittens. The experiment consisted of having two kittens move about an environment, with each receiving identical visual information. However, one of the kittens was carried passively through the environment in a gondola, while the other was free to walk. The kittens were subsequently removed from the testing environment, held in the air, and then lowered to a tabletop to see if they would exhibit a normal foot-placing response. As it turned out, only the kitten that was able to walk freely through the environment was able to produce the adaptive foot-placing behavior. It was concluded that moving passively through the testing environment in the gondola rendered the kitten unable to correlate the visual information of the approaching table with the appropriate motor commands. However, the kitten that walked through the environment learned to directly relate its movements with corresponding visual changes (Held, 1965). In conclusion then, it would appear that neither movement alone, nor vision alone, provide adequate information to ensure successful navigation through the environment.

Perturbation studies have also furthered the understanding of locomotion and the importance of sensory feedback. Eng, Winter, and Patla (1994) investigated movement reorganization strategies following a tripping perturbation applied early or late in the swing phase of locomotion. In this study, subjects were required to walk along an 11m pathway at their natural pace. During the course of a trial, an 8cm obstruction was unexpectedly introduced at either 20% or 60% of the swing phase, resulting in the foot making contact with the obstruction. In general, it was found that when the perturbation was introduced early in the swing phase, an elevating strategy, comprised of increased flexion of the swinging leg and increased extension of the stance leg, was employed to help recover stability following the trip. Also, the stance leg was raised in early heel-off to further lift the subject over the obstacle. Conversely, when the perturbation was applied late in the swing phase, a different strategy was used, involving a rapid lowering of the swinging leg and a shortening of the step length. Therefore, the authors concluded that reflex responses to perturbations are phase-dependent to ensure functionally appropriate corrections to unexpected obstacles. These findings suggest that each phase of the gait cycle is associated with an invariant pattern of muscle activation generated at the spinal cord level.

Additional studies of obstacle avoidance have shown that lower limb trajectories can be modulated as a function of obstacle height and width (Patla & Reitdyk, 1993), or obstacle fragility (Patla, Reitdyk, Martin, & Prentice, 1994). In general, visual feedback of the obstacle properties resulted in proactive adjustments in the locomotor pattern. Moreover, Patla et al. (1994) showed that not only were subjects aided by vision of their environment, but also by seeing their limbs move through the environment. For example, it was found that compared to the leading leg, there was greater variability in toe clearance for the trailing limb. The authors interpreted this increase in variability in the trailing limb to a lack of visual exproprioception.

2.2 Research Relating to the Movement of the Upper Limbs

The upper limbs allow human beings to carry out a great number of activities. From sign language, to handwriting, to simple gestures, a prime role of the arms and hands is to communicate. In addition, many forms of artistic expression, from sculpture to playing a musical instrument, are realized to a large extent through manipulations of the hands and fingers. Although somewhat less exotic, everyday tasks from dialing a telephone to holding a coffee cup are likewise made easier due to our ability to aim at and grasp objects. Motor behaviour research has examined at length each of the previously mentioned activities. What follows is a general discussion of constraints on human hand movements, as well as a more directed review of how constraints influence such upper limb activities as pointing and prehension.

An important issue related to the study of human movement is the notion of constraints. Constraints have been defined as variables that limit the way in which movements can be controlled and executed (Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987). At the outset, it is noteworthy that such a broad definition could prove troublesome from an experimental standpoint. Fortunately however, several lines of investigation have attempted to clarify and quantify the issue of movement constraints in laboratory settings. An early investigation specifically designed to examine movement constraints was conducted by Marteniuk et al. (1987). These authors measured the three-dimensional movement trajectories of participants under three different experimental conditions: 1) pointing to a target with the index finger versus grasping a disc of the same size, 2) grasping a fragile object (light bulb) versus a non-fragile object (tennis ball), and 3) grasping a disk and either placing it in a tight-fitting well, or throwing it into a large box. The results of this study yielded several interesting findings. First, it was found that participants produced different movement trajectories depending on whether or not the goal of the task was pointing to a target or grasping a disk. More specifically, it was noted that the increased hand movement requirements of grasping led to a lengthening of the deceleration phase of the movement. Second, when the objective of the task was to fit a disk into a tight-fitting well (versus throwing the disk into a large box), a lengthening of the deceleration phase was again noted. Lastly, the authors found that increasing the perceived fragility of an object also influenced the trajectory of the movement. Although this last result failed to reach statistical significance, the trend of the data was such that grasping a light bulb resulted in a longer deceleration phase than when grasping a tennis ball. The kinematic features of the movements, particularly the deceleration component, indicated that the precision requirements of the task constituted a significant constraint on the planning and control of upper limb tasks (Marteniuk et al., 1987).

The aforementioned results could all be considered to be the product of task-specific constraints (MacKenzie & Iberall, 1994), in that the adjustments seen in the movement trajectories arose from manipulations to the task goal (point or grasp), object properties (fragile, non-fragile), or intention (careful placement versus throwing) of the movement. It is true that not all constraints are task-specific, however, such variables as motivational levels and perceptual abilities are somewhat more ambiguous and difficult to quantify. Therefore, for the sake of consistency, the following sections of this paper on pointing and grasping will be limited to those task-specific constraints that can be carefully manipulated in controlled experimental settings.

2.2.1 Pointing and Aiming

Literature on pointing and aiming has revealed an important movement constraint regarding the speed/accuracy requirements of the task. Woodworth (1899) was the first to observe experimentally that visually-guided movements were less accurate when performed quickly. As Woodworth stated: "It is clear that the study of accurate movement must consider at every step the speed of the movement. Two movements are not necessarily the same because they have the same length. If one is more rapid than another, a factor is introduced which will very conceivably affect the accuracy" (1899, p.27). Fitts (1954) went on to quantify the speed/accuracy relationship by demonstrating that movement time changes as a linear function of the index of difficulty (ID) of the task. Calculations of the indices of difficulty were made using the equation $ID = \log_2(2A/W)$, where A was the amplitude of the movement and W was the width of the target. Fitts (1954), using a reciprocal tapping task, discovered that for each category of target width, movement time increased progressively as movement amplitude increased. Likewise, for each category of amplitude, movement time increased as target width decreased. These results clearly indicated that accuracy requirements constrain pointing movements, and that accuracy was a function of both the amplitude and width of the target. Conversely, with all other things being equal, it was clear that the speed requirements of a task constrain a movement, as evidenced by decreases in accuracy (Woodworth, 1899; Fitts, 1954).

Adding additional movements to a pointing task, walking for example, adds another dimension that likewise constrains the pointing task. Marteniuk, Ivens, and Bertram (2000) conducted a study in which subjects performed a pointing task both while standing and while walking past targets of varying sizes and amplitudes. Analysis of hand and torso kinematics yielded several interesting findings. First, when the pointing hand was analyzed in terms of a room-centered frame of reference, it was difficult to distinguish between the walking and standing conditions of the task. However, when the hand was considered using the body as a moving frame of reference, it became clear that performing the task while walking resulted in vastly different arm trajectories. A particularly interesting aspect of these findings was that despite the different trajectories between walking and standing, the movements were performed with equivalent degrees of speed and accuracy. Therefore, while walking introduced an additional constraint to the task, it did not result in any decrement in pointing performance.

MacKenzie, Marteniuk, Dugas, Liske, and Eickmeier (1987) presented a kinematic explanation for Fitts' law by demonstrating that smaller targets resulted in subjects spending more time in the deceleration phase of the movement. These authors further suggested that skewing of the velocity profile originated in the planning of movements, and was then extended on the basis of visual feedback. It should be noted that feedback, or the availability of feedback is also a possible constraint on movement. In most cases, availability of feedback is not an issue, but under certain circumstances sensory feedback is not always abundant. It is also possible that movements may be too fast to allow time to process feedback even if it is available. These issues will be discussed in greater detail later in this paper.

2.2.2 Prehension

For several reasons, prehension is susceptible to more movement constraints than are simple pointing movements. First, as Marteniuk et al. (1987) noted, prehension movements are inherently more complex and are therefore more constrained than aiming movements. In addition, careful consideration of prehensile maneuvers reveals that constraints must be regarded on two levels. Jeannerod (1981, 1984) introduced the idea that prehensile movements were comprised of two phases: an initial high velocity phase followed by a slow velocity phase. Based on correlations between time of peak deceleration of the wrist and time of peak aperture, Jeannerod (1984) further suggested that the transport and grasp components of the movement were temporally coupled. This coupling, according to Jeannerod, was the result of a central plan or program that was organized to ensure smooth execution of the two separate components in a single, coordinated act. Although this central planning notion has been challenged (e.g., Marteniuk, Leavitt, MacKenzie, & Athenes, 1990), the functional linkage between the reach and the grasp cannot be denied. A final observation of note reported by Jeannerod (1984) was that certain task manipulations differentially affected the two components of prehension. For example, it was shown that varying the distance of a to-be-grasped object from a subject resulted in an increase in peak wrist velocity, while grasp measures remained constant. Conversely, when the *size* of the object was manipulated, increases in peak aperture were noted, while transport kinematics were unchanged. These findings prompted Jeannerod to postulate the existence of independent visuomotor channels for the transport and grasp components of prehension. From this, it followed that the visuomotor channel for transport was activated by information regarding *extrinsic* object properties (e.g., distance, orientation), while the visuomotor channel for grasp was sensitive to such *intrinsic* object properties as size or shape (Jeannerod, 1981).

In terms of constraints then, it is apparent that specific object properties can constrain the prehensile act in different ways. Many researchers in the years since Jeannerod's original work have added to and amended the concept of independent visuomotor channels. For example, Marteniuk et al. (1990) found that for each 1 cm increase in object size, the maximum grip aperture increased by 0.77 cm. Paulignon, Jeannerod, Mackenzie, and Marteniuk (1991a) visually perturbed object position to investigate movement reorganization following unexpected changes. The logic was that because object position is an extrinsic property, perturbing position should only affect the transport component of the movement. Subjects in the study were told to reach for and grasp one of three dowels. On certain trials, initial arm movement caused the dowel to instantaneously change its location to one of two adjacent positions. These perturbed trials were then compared to control conditions to analyze the kinematic adjustments. Somewhat surprisingly, the findings of this study indicated that perturbing object position resulted in adjustments to both the transport and grasp components of prehension. This result puts into question the proposed independence of the two visuomotor channels, as suggested by Jeannerod (1981, 1984).

Paulignon, Jeannerod, MacKenzie, and Marteniuk (1991b) conducted a similar study in which visual perturbations were induced on object size. In this study, selective perturbations of dowel size were randomly introduced at the outset of the reaching movement. The reasoning behind this study was that perturbations to the intrinsic property of object size should only affect the grasp, leaving the transport component unchanged. The authors discovered however, that perturbing object size resulted in corrections to both the transport and grasp components of prehension. Similar to the finding of Paulignon et al. (1991a), these results seemed contrary to the notion of independent visuomotor channels. Instead, Paulignon and his colleagues (1991b) suggested that in addition to the separate parameterization of transport and grasp, an additional mechanism exists whereby a desired position (i.e., a goal) was centrally encoded at a higher level in the planning hierarchy. Although elaboration on this idea is beyond the scope of this paper, the point that constraints are not necessarily component-specific is well taken. The implication is that constraints affect the *method* of achieving a goal, and that the human motor control system can be coordinated in countless ways to ensure that tasks are successfully completed.

2.3 Research Relating to the Combination of Upper and Lower Extremity Task

Now that the individual activity systems of the upper and lower limbs have been discussed, we can now focus on how these two systems have been shown to interact experimentally. To date, associations between the upper and lower limbs have been investigated from both a functional and a neurophysiological level. From the functional perspective, Jackson, Joseph, and Wyard (1983a, 1983b) sought to answer several questions regarding the role of upper limb activity in walking. Namely, do the arms move consistently throughout locomotion? If so, is the movement of the upper limbs passive, or is it under active control? In the first of two published works, Jackson et al. (1983a) showed remarkably similar within-subject movement patterns in the upper limbs, even when subjects were required to walk at different cadences. More specifically, it was noted that during locomotion the upper arm tends to spend a greater percentage of time in extension than in flexion. Further, the authors showed that this trend becomes even more apparent as cadences slow, to the point where the upper arm does not go into flexion until just prior to contralateral heelstrike (Jackson et al., 1983a). Extending upon this work, Jackson and his colleagues (1983b) sought to explain the *function* of the arm swing during locomotion. To this end, the authors offered three possibilities: 1) it decreases the total energy cost of locomotion, 2) it counteracts the rotation of the pelvis about the longitudinal axis, and thereby stabilizing the head and eyes, and 3) without muscular control of the upper limbs, walking would be jerky and uncoordinated. The authors filmed subjects while walking normally, walking while carrying a book in front of them, walking while voluntarily holding their upper limbs stationary by their sides, walking with their arms strapped to their sides, and attempting to walk with their arms in phase with the ipsilateral lower limb. Their results indicated that the most tenable possibility regarding the function of the upper limbs during walking was to produce smooth, non-jerky locomotion. Further, the authors suggested that that the motion of upper arms may be under the control of a rhythm generator (Jackson et al. 1983).

From a neurophysiological perspective, Georgeopolis and Grillner (1989) suggested that the neuronal systems responsible for reaching and locomotion might have a common evolutionary basis. These authors noted that in cats, the contribution of the motor cortex to the initiation of a reaching movement descends through an interneuronal system at the C3-C4 level of the spinal cord. These interneurons relay the commands to proximal neuronal pools, which in turn activate motoneurons. Interestingly, it was discovered that blocking the output at the level of the neuron pools results in disruptions to both reaching and precision walking. These results would seem to imply a neurological basis for a functional linkage between the hindlimbs and forelimbs in cats.

Previously, Muzii, Lamm, Warburg, and Gentile (1984) reported a similar linkage between the hands and feet in a combined walking and clapping task. These authors discovered that hand clapping is tightly coupled with heelstrike when both are performed at preferred rates. Furthermore, Muzii and his colleagues (1984) noted that when subjects were instructed to walk and clap at different rates (i.e., walk fast/clap at preferred rate or walk at preferred rate/clap fast), they were unable to decouple the strong functional linkage. It was concluded that the temporal patterning of the clap cycle could be dictated by the step cycle. Carnahan, McFayden, Cockell, and Halverson (1996) showed similar findings in a combined walking/prehension task. In this experiment, subjects were asked to pick up either a small or large object as they walked past a table. The authors noted that gait kinematics remained surprisingly consistent throughout the task, regardless of whether subjects were reaching for a small or large object; however, the upper limb reflected the experimental manipulations in object size. The results led the authors to postulate the existence of a movement hierarchy, whereby the stability of gait supercedes the stability of prehension (Carnahan et al., 1996).

In possible contradiction to the findings of Carnahan et al (1996), Bertram, Marteniuk, and Wymer (1999) showed that performing a prehension task while walking not only affects the upper limbs, but the forward speed of the body as well. In this study, subjects were required to walk alongside a table, pick up a glass of water (either covered or uncovered) and transport it to one of two targets (one large, one small) 30 cm anterior to the lift off point. The authors noted that removing the lid from the cup resulted in subjects slowing their forward progress to accommodate the precision requirements of the task. Similar results were obtained when the subjects were required to place the cup (either covered or uncovered) on the smaller target. It should be noted that Bertram et al. (1999) used chest velocity and not lower limb kinematics to measure rates of locomotion. Therefore, it is possible that the slowing of the forward velocity was not indicative of lower limb activity, but rather of a postural adjustment at the level of the torso.

2.4 Trunk-Assisted Prehension Literature

We turn now to the second type of experiment that is pertinent to our discussion of multi-segmental coordination by examining the relationship between the torso and arm during trunk-assisted reaching experiments. Prehensile situations often require that the torso become involved in the movement. Exactly how the trunk and arm work together in this kind of situation has been the subject of recent experimentation. Ma and Feldman (1995) found that when they asked subjects to move their torsos either forward or back during a reach, hand trajectories were virtually identical to when they made the same movements using only the arm. Furthermore, they discovered that torso movement generally preceded the movement of the hand and continued after the hand had reached its target. These findings led the authors to suggest that reaching movements involving the torso involve two functionally different synergies. One synergy was said to coordinate the muscles and joints of the hand, while the other was left to coordinate the trunk and arm together, thereby resulting in a consistent endpoint position of the hand (Ma & Feldman, 1995).

Saling, Stelmach, Mescheriakov, and Berger (1996) conducted an experiment in which subjects were to reach for and grasp dowels (large or small) placed at such a distance so as to require the forward flexion of the torso for a successful grasp. These authors found further evidence to suggest the presence of independent synergies working together to produce consistent hand trajectories. Specifically, it was noted that the transport and aperture components remained temporally coupled despite the addition of the torso to the movement. Conversely, there was no such coupling between the trunk movement and the grasp, in that the action of the torso was the same regardless of the size of the dowel. Furthermore, the fact that the trunk kinematics did not reflect the accuracy constraints of grasping a smaller dowel provided further evidence for the notion of independent control mechanisms for the arm and for the torso (Saling et al., 1996). However, the suggestion of Saling et al. (1996) that torso kinematics are somehow resistant to task accuracy constraints has been challenged in the literature. For example, Wang and Stelmach (2001) showed that in fact the movement of the torso could be modulated when subjects reached to grasp objects of differing size. Moreover, an earlier experiment by Steenbergen et al. (1995) showed that under certain conditions, the torso kinematics could be affected by the accuracy requirements of a task. These authors found that the displacement of the torso significantly increased when subjects reached to grasp cups full of coffee compared to when they reached for empty cups. This result raises an obvious question. Namely, why is torso movement affected by certain constraints, but not others?

A closer examination of the trunk-assisted reaching literature may provide an answer. To recall, Saling et al. (1996) had subjects reach to and grasp one of two dowels (one large, one small). It was concluded that the task constraint of object size affected the transport and grasp components of the upper limb movement, while the trunk remained unaffected. A possible alternative explanation for these results could be that the methods employed by Saling et al. (1996) (i.e., big dowel/little dowel) did not affect task complexity in such a way so as to elicit significant torso contributions. Therefore, one might expect that if a trunk-assisted reaching study were designed in which one of the experimental task conditions was significantly more difficult than the other, differences in the torso would become apparent. Along with Wang and Stelmach (1996) and Steenbergen et al. (1995), two more recent experiments from our lab confirm this assertion. First, Mackey et al. (2000) conducted a trunk-assisted reaching study in which subjects were required to either reach for and grasp, or transport cups of water to targets within and beyond the arm's length. For half the trials, the cup of water was covered while for the other half the lid was removed. Among the results of this study was the finding that removing the lid from the cup resulted in a significant increase in forward torso displacement. This finding supports the Steenbergen et al. (1995) suggestion that when necessary, added torso movement allows for a more stable movement. Steenbergen et al. (1995) suggested that this is accomplished by reducing the movement at the shoulder and elbow joints (i.e., joint-freezing).

Of further interest is not only how the arm and the torso segments move individually, but also how they move in relation to one another. Bertram, Mason, Mackey, MacKenzie, and Marteniuk (2000) represented the spatial trajectories of wrist movement in terms of both world-centered and body-centered coordinates. Figures 2A and 2B show the spatial path plots of the wrist for a representative subject in x (horizontal) and z (vertical) coordinates in the reach-to-grasp task.

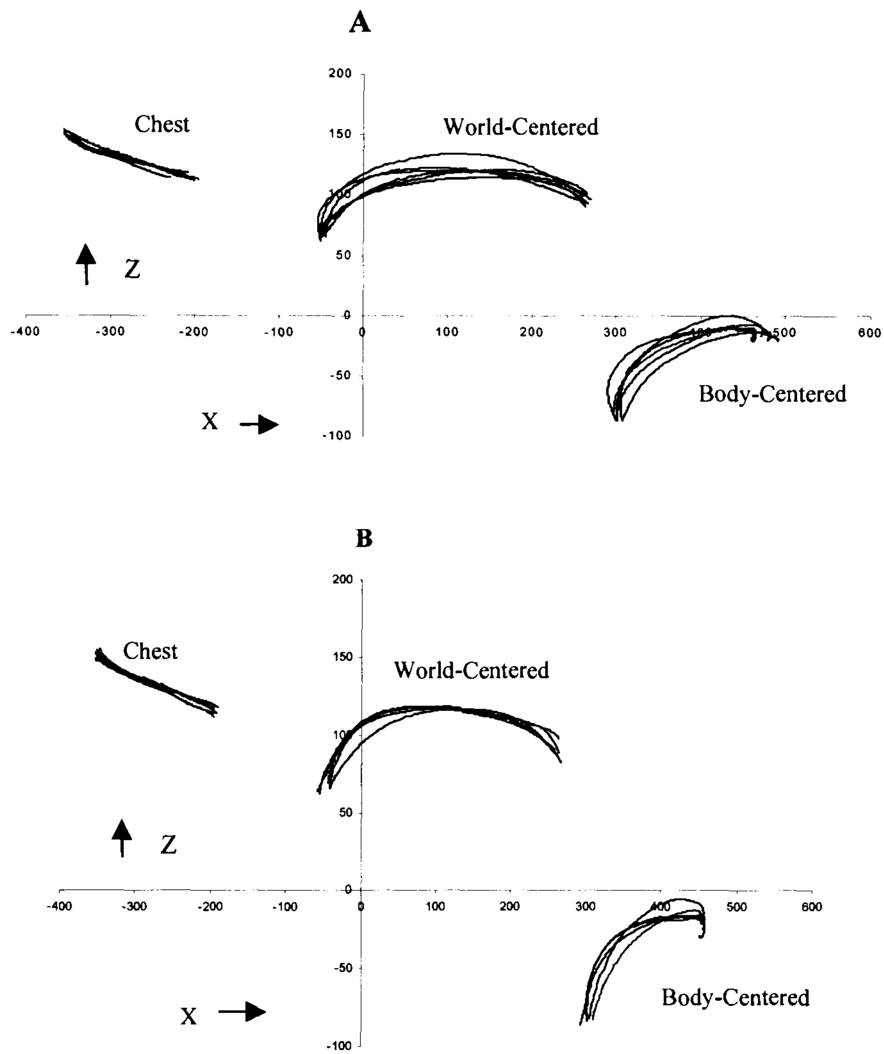


Figure 2: Spatial path plots for a representative subject depicted the vertical (z) and horizontal (x) displacement of the chest and wrist during a reach to grasp task

From a world-centered viewpoint, Figure 2A (reaching for a covered cup) shows quite a large degree of variability in the vertical (z) direction of the movement. Furthermore, the body-centered plots show substantial variability in terms of the final x position, indicating a variable torso contribution from trial to trial. Figure 2B however (reaching for an uncovered cup) shows that in body-centered coordinates, there is less variability in the x direction. Therefore, even though the torso was moving significantly further when the cup was uncovered, its movements were more consistent on a trial to trial basis. This consistency is reflected in the more tightly grouped world-centered, or endpoint trajectories. These qualitative results seem to reflect a concerted effort on the part of the motor control system to more tightly coordinate the arm and torso under more complex task conditions. An important note pertaining to these observations of variability is that they are based solely on the visual inspection of x-z displacement plots. Although the authors reported some statistical evidence that showed differing torso contributions across levels of complexity, there is no direct quantification of the variability within or between conditions. This important issue is one that we hoped to address more precisely later in the dissertation.

2.5 Motor Equivalence

The issue of motor equivalence has been, and will continue to be, discussed throughout the course of this paper. It is worthwhile at this point to examine this concept more thoroughly and elaborate on exactly how motor equivalence has been historically investigated. Although it is unclear who first advanced the notion of motor equivalence, Lashley (1930) is generally regarded as the first to note the phenomenon at any length. From its original description in mere conceptual terms, motor equivalence has come to be defined in motor control circles as a variable means to an invariant end (Abbs, Gracco, & Cole, 1984). In other words, it is the way in which consistent voluntary movements are reproducible across an infinite variety of initial conditions and environmental contexts (Munhall, 1986). Bernstein had this to say on the subject: "If we turn from the simplest and most repetitive actions to more complex purposeful movement...such broad variations in the motor composition of movements becomes the universal rule" (p. 132-133).

An everyday and often cited example of motor equivalence can be seen in human handwriting. Specifically, whether a person is writing small words on a regular piece of paper, or writing those same words more largely on a blackboard, the letters of the words maintain a characteristic form (Merton, 1972). This consistency occurs in spite of the fact that different muscle groups are being used and different forces are acting upon the hand and arm in each task. Other examples of motor equivalence abound in motor control literature. Some of the most convincing evidence comes from the work of Abbs et al. (1984) on speech perturbation. These authors noted that when one of the speech articulators (i.e., upper lip, lower lip, jaw) was unexpectedly loaded, the speech system readily compensated for the perturbation, resulting in the successful completion of the phonetic goal. More importantly, compensation for unexpected load was not only seen at the site of the perturbation, but in the system in general. For example, if a load was applied to the lower lip during the production of a sound, corrections were seen not only in the lower lip itself (termed autogenic), but in the upper lip as well (termed non-autogenic). Similar compensations were observed when loads were added to the upper lip and the jaw muscles. These remote adjustments suggested a feedforward coupling between the various articulators involved in the movement (Abbs et al., 1984).

Results similar to those demonstrated by Abbs et al. (1984) have also been reported in the reaching and grasping literature. Cole, Gracco, and Abbs (1984) applied unanticipated loads to the thumbs of subjects during a pinching task involving the thumb and forefinger. These authors discovered that the perturbations were compensated for by increased flexion of the thumb, and/or by increased flexion of the forefinger. In any event, the subjects consistently managed to achieve the required grip force, thus successfully completing the task. Furthermore, the response latencies reported by Cole et al. (1984) of the forefinger were between 60 and 90 ms – similar to the non-autogenic or feedforward corrections reported by Abbs et al. (1984) for speech articulators and by Traub, Rothwell, and Marsden (1980) for the wrist and hand.

Further empirical evidence for motor equivalence was provided by Paulignon et al. (1991b). These authors perturbed the location of a to-be-grasped object during a prehension task. The results of this study showed that wrist, which was not active during the control trials, assisted with the grasp when the object location was perturbed. In both cases, successful grasps were achieved, thus demonstrating once again how variable means can produce the same successful result.

Another way in which motor equivalence has been investigated is by looking for covariance in the segments involved in multiarticular movements. Cole and Abbs (1985) observed both the location of contact, and contact pressure for the thumb and forefinger in a rapid pinching task. Over a series of trials, it was first found that although there were variations in the positions of the thumb and finger at the time of contact, the contact pressure (i.e., the goal of the task) was nonetheless within the criterion range. Furthermore, along with the natural variations in contact position, it was found that as the two-dimensional position of the distal thumb surface varied, there were corresponding variations in the two-dimensional position of the distal forefinger surface (Cole & Abbs, 1985). These results, similar to those mentioned noted earlier for speech perturbation research, indicated that the trajectories of the individual movement segments are subordinate to the higher level motor goal. In a locomotion experiment, Winter (1984) found similar patterns of covariation in joint torque resulting from the reciprocal actions of the muscles about the knee. More specifically, Winter (1984) suggested that although gait patterns exhibit consistent kinematic patterns during locomotion, the means by which the muscles of the leg act to produce those patterns is highly variable.

An important premise that underlies each of the above experiments is that motor equivalence is a task-specific phenomenon. In other words, additional motor segments act in a compensatory role only when a task requires such compensation. This point may seem trivial, but its importance lies in the fact that motor equivalence provides the necessary flexibility for the motor control system to carry out goal-oriented movement in a dynamic environment. For example, the compensatory action of the articulators for speech production shows that not only are the articulators coupled, but that the coupling is sensitive to the evolving behavioural state of the system.

Chapter 3: Experiment 1

Does adding complexity to an upper limb task result in gait adjustments?

3.1 Introduction

Coordinated human locomotion relies on the vast interplay of sensory feedback and the proper sequencing of the involved muscle groups. Even as one walks across the smoothest terrain, the muscle activity of one leg, and reciprocal activity in the other, must both continuously respond and react to the ever-changing world through which we travel every day. Often overlooked in this complicated lower limb activity is the role played by the arms during locomotion. Jackson et al. (1983b) suggested that the arms act during locomotion to aid in the production of smooth, non-jerky motion during walking.

Oftentimes as individuals interacting with the world around us, we are required, either for the sake of efficiency or necessity, to interrupt this smooth trade-off between the arms and legs to use our hands for some specific purpose while we are in motion. Anyone who has seen a wide receiver in a football game catch a pass while streaking down the sideline knows that athletes seem particularly adept at completing such maneuvers. Though less glamorous, every day tasks such as picking up a glass while walking past the kitchen counter, or carefully dropping a crumpled ball of paper as one passes by a trash can still require a great deal of coordination.

Recently, researchers have begun investigating the motor control processes involved in combined tasks involving the upper and lower extremities. Carnahan et al. (1996) had subjects pick up large and small cylindrical objects while walking in order to determine if gait patterns were disrupted or altered as a result of having to use the hands while walking. These authors found that although adjustments were seen in the kinematics of the hand and arm when subjects had to pick up the smaller object, the gait patterns remained unchanged. These findings prompted the authors to suggest that a movement hierarchy may be at work, whereby the stability of gait supercedes the stability of prehension.

In partial contradiction to the work of Carnahan et al. (1996), Bertram et al. (1999) found, in a similar experiment, that when subjects were to grasp full, uncovered cups of water, their forward velocity was slower than when the same subjects reached for covered cups of water. Bertram et al. (1999) suggested that the differing conclusions of the two studies were due to the nature of the prehension tasks. More specifically, the to-be-grasped objects in the Carnahan et al. experiment (1996) were pencils and aluminum cans – two objects that differed very little in terms of complexity for the motor control system. By introducing a "spillability" factor in uncovered versus covered cups of water, Bertram et al. (1999) added a significant change in terms of the between-condition complexity and suggested that this difference was what accounted for the altered gait patterns. A possible shortcoming of the Bertram et al. (1999) experiment was that no standard gait measures were reported. Instead, these authors looked only at the forward velocity of the body as it moved throughout the task. Therefore, it could be suggested that the observed slowing was due to postural adjustments (i.e., trunk extension or rotation) and not true gait adaptations. The purpose of Experiment 1 then, was to partially replicate the methodology of Bertram et al. (1999), and to attempt to specifically quantify the gait adjustments, should any be occurring.

3.2 Methodology

3.2.1 Participants

Thirteen subjects (Simon Fraser University students; 7 males and 6 females) were included in the analysis. All subjects were right-handed and had normal or corrected-to-normal vision. Prior to participation, subjects completed informed consent forms that indicated that the experiment had been approved by the University Ethics Committee. Subjects received an honorarium of ten dollars for their participation in the one experimental session of approximately one hour in duration.

3.2.2 Apparatus

The OPTOTRAK 3-dimensional camera system (Northern Digital, Waterloo, Ontario) was used to measure the subject's movements via the position of infrared emitting diodes (IREDs) placed at strategic anatomical landmarks. Subjects were also instrumented with a set of footswitches (B&L Engineering, San Francisco) which were placed into a pair of slippers that each subject wore throughout the course of the experiment. As each subject walked during a given trial, the pressure generated during a stance phase of locomotion resulted in a closing of the switch. When the foot was lifted during toe-off to start the swing phase, the switch was then opened and a change in velocity was registered. Following standard phases of locomotion, the time from heelstrike to ipsilateral toe-off was considered the stance phase. Conversely, the time between toe-off and ipsilateral heelstrike was measured to be the swing phase (Winter, 1989).

A plastic cup filled with water was the object to be grasped and transported. When it was covered, the cup measured 8.9 cm high, 6.0 cm in diameter at the top, and

4.5 cm in diameter at the bottom. When the lid was removed from the cup, it measured 8.6 cm high, 5.5 cm in diameter at the top, and 4.5 cm in diameter at the bottom. The mass of the cup was 91.7g when covered, and 86.2g when uncovered. A table (120 cm x 75 cm x 75 cm) was used as the subjects' working surface. Two laboratory jacks were used to customize the working surface for each subject's height. Specifically, when the cup sat in the starting position, the laboratory jacks were raised or lowered so that the top of the cup was aligned with the lateral epicondyle of each subject's right arm. The cup's initial position was on a metal plate (5 cm in diameter) that sat affixed to the top of a laboratory jack on the table. Another identical metal plate was placed on the second laboratory jack that was then placed at one of three distances (15 cm, 30 cm, or 45 cm) anterior to the first jack. A metal washer was attached to the undersurface of the cup so that cup lift and cup placement could later be determined by the breaking or completion of a circuit. Figure 3.1 depicts the general set-up for the experiment.

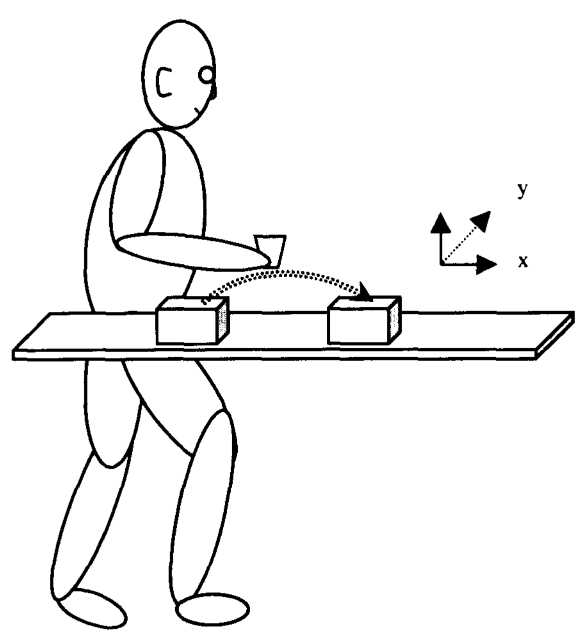


Figure 3.1: Experimental set-up.

3.2.3 Procedure

Upon arriving in the laboratory, each subject was instructed to read and sign an informed consent. Each subject was then given time to read an instruction sheet in order to familiarize themselves with the experimental procedure. If there were no questions or concerns, the subject was then instrumented with six IREDs: three on the torso and three on the right hand. The torso IREDs were used to provide information regarding the independent trunk movement throughout the task, as well as to help determine the motion of the hand relative to the torso during the task (Marteniuk & Bertram, 2001). The torso IREDs were affixed to a Velcro strap that could be wrapped around the subject's chest, so that when the strap was fastened the three IREDs formed an L-shape over the subject's sternum. The remaining three IREDs were placed on the skin above the styloid process of the radius, and the nails of the right thumb and index finger. The 3-dimensional positions of the IREDs over time was sampled at a frequency of 200 Hz. Next, the subject put on a pair of slippers that contained the footswitches and were given a few minutes to get accustomed to moving around the room.

The task was to walk approximately 2 m to a table that was placed parallel and to the right of the subject's walking path, pick up a cup of water, transport that cup to a target, place the cup on the target, then continue walking for approximately 1.5 m. The subjects were given instructions to keep walking throughout the course of the task at a pace that they deemed comfortable. The three target locations for cup placement were located at 15 cm, 30 cm, or 45 cm in front of the cup's starting position. Subjects were asked to grasp the cup near its top edge so that the IREDs would remain in view of the camera throughout the trial. Finally, we asked that subjects transport the cup to the target as quickly and as accurately as they could. If the cup was uncovered, we asked that the movement be made as quickly and as accurately as possible without spilling the water. Each subject was given six practice trials (three with the cup covered and three with the cup uncovered) prior to begin the experimental trials. For half of the experimental trials, the cup of water was covered and therefore resistant to spilling. For the other half of the trials, the lid was removed from the cup. If any water was spilled on any trial, that trial was redone, and the error was noted.

The above yielded a 2 Cup (covered, uncovered) X 3 Amplitude (15, 30, and 45cm) within-subjects design. Ten trials were performed in each condition in a blocked manner. The order of the conditions was randomized across all subjects. Thus, each subject performed a total of 60 trials. Testing time was approximately one hour.

3.2.4 Data Processing and Analysis

At the completion of each experimental session, the data files for each trial were transferred from the IBM-PC to a Sun workstation for analysis using WATSMART and WATSCOPE programs. OPTOTRAK files missing four or less consecutive frames were interpolated, while those files missing more than four consecutive frames within the movement time were discarded. In order to define a meaningful frame of reference, the data were rotated to the work space of the task such that the principal (i.e., forward) axis of movement was defined as the positive x-dimension, lateral movement was defined as the y-dimension, and the horizontal movement was denoted as the z-dimension. The data were then filtered using a Butterworth dual-pass filter at 8Hz in order to reduce any distortion that may have been picked up in the movement recording process.

Because the task consisted of two phases, a reach-to-grasp (i.e., approach) phase and a transport phase, the analyses were divided accordingly. The "approach" phase was defined as the time from when the IREDs of the hand were first visible to the camera, until the cup was lifted. Because the point in time at which the IREDs first became visible differed from trial to trial and subject to subject, visual inspection was used to determine a standardized start point for all subjects. Based on this inspection, a cut-off point of 200 frames, or one second prior to cup lift, was used to determine the start point for the approach phase. The "transport" phase then, was defined as the time from when the cup was lifted until it was replaced on the target position.

Regarding the approach phase, the dependent measures of interest regarding upper limb movement were peak velocity (PV) and time after peak velocity (TaPV). It should be noted that because the arms were in continuous motion during the last second prior to cuplift, the peak velocities reported herein represent only that peak which occurred in the last second of sampled data. Furthermore, because it is conceivable that the peak velocity of the approach phase could have occurred at a time prior to the one second cutoff, the data underwent an initial visual inspection to ensure that indeed the velocity profiles demonstrated an abbreviated bell-shape, and that a peak occurred sometime during the final second. Lastly, because the reach-to-grasp or approach phase of this task had no definitive spatial or temporal starting point, the reported measure of time after peak velocity could only be given in absolute terms.

Regarding the transport phase, the dependent measures of interest were as follows: Movement time (MT), peak velocity (PV), time to peak velocity (TPV), percent time to peak velocity (%TPV), time after peak velocity (TaPV), and percent time after peak velocity (%TaPV). Movement time was defined as the time from cup lift to the time of cup replace, as determined by voltage changes at the contact plates. Velocity profiles were obtained by differentiating the OPTOTRAK position data in x, y, and z coordinates via the central finite difference technique. Resultant velocities were then calculated using each of the x, y, and z velocities. Finally, peak velocity (mm/s), times to and from peak velocity (ms), and relative time to and from peak velocity (%) were then obtained from these velocity profiles.

Several comparisons of gait characteristics were also analyzed. First, a comparison of stance times leading up to cup lift were analyzed for each condition to examine whether or not subjects were using a consistent gait pattern leading up to cup lift. Second, of particular interest were the differences in gait that resulted from the adding of complexity to the prehension task. Specifically, the following comparisons were analyzed across the covered and uncovered cup conditions: stance time at the time of cup lift (ms), contralateral swing time at cup lift (ms), stance time at cup replace (ms), contralateral swing time at cup replace (ms).

3.3 Results

A complete list of all statistical tests with means and standard deviations (or standard errors) for Experiment 1 is presented in Appendix A.

3.3.1 Wrist Kinematics

The results of the upper limb kinematic data are presented in two sections. The first section deals with the hand as it reached to grasp the cup during locomotion. For this first set of analyses, only the 200 frames, or 1 second, of data prior to cup lift were considered. For that reason, no movement time data are presented. Therefore, only peak velocity and time after peak velocity will be reported for this first phase of the movement. The second set of analyses deal with the time during cup transport, or from cup lift to cup replace. Each dependent measure was analyzed separately using 2 cup (covered, uncovered) X 3 amplitude (15cm, 30cm, 45cm) repeated measures ANOVAs. Post hoc procedures were carried out using Tukey's HSD (α=.05). Huynh-Feldt epsilon was evaluated to determine whether the repeated measures data met the assumption of sphericity (>.75). Because the sphericity assumption was met for each variable, we used the univariate tests to maintain power.

3.3.1.1 Approach Phase

A significant cup main effect was found for peak velocity as subjects reached to grasp the cup during locomotion ($F_{1,12}$=24.84, p<.001). More specifically, it was found that greater peak velocities were achieved when subjects reached for covered versus uncovered cups (see Figure 3.2).

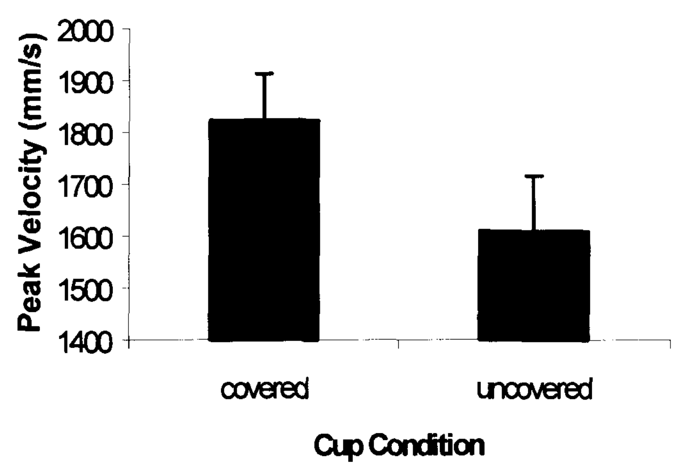


Figure 3.2: Mean peak velocity (with standard errors) of the wrist as subjects reached to grasp covered and uncovered cups.

In terms of the time spent from peak velocity to the time when the cup was lifted, a significant cup x amplitude interaction was found ($F_{2,24}$=4.11, p=.03) (Figure 3.3). Post-hoc tests showed that the interaction was due to the difference between the covered and uncovered cups being larger for the 45cm amplitude than for the other two amplitudes.

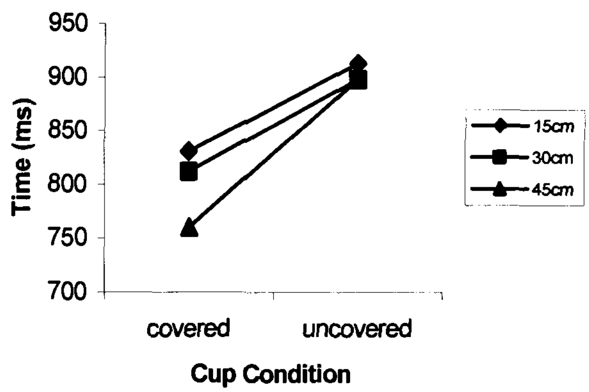
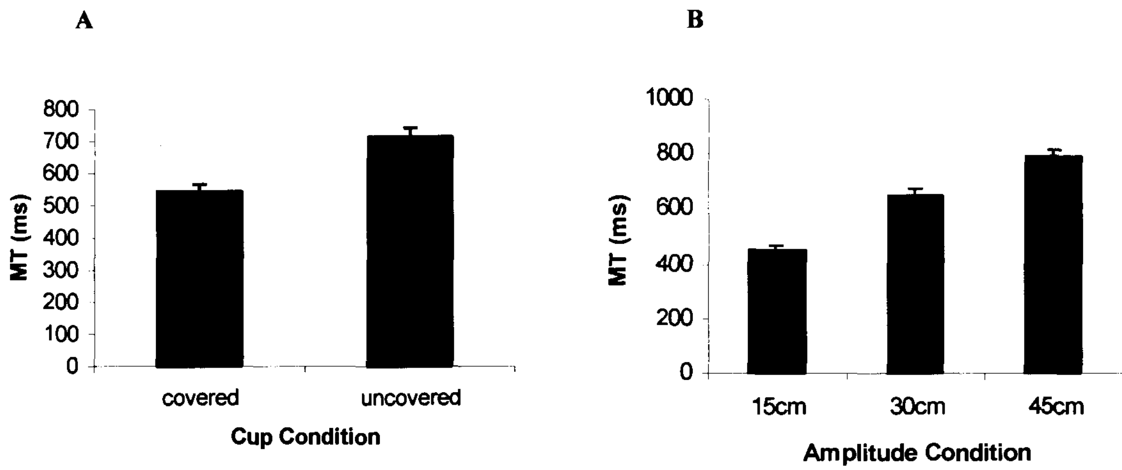


Figure 3.3: Cup X amplitude interaction for mean time after peak velocity as subjects reached to grasp covered and uncovered cups.

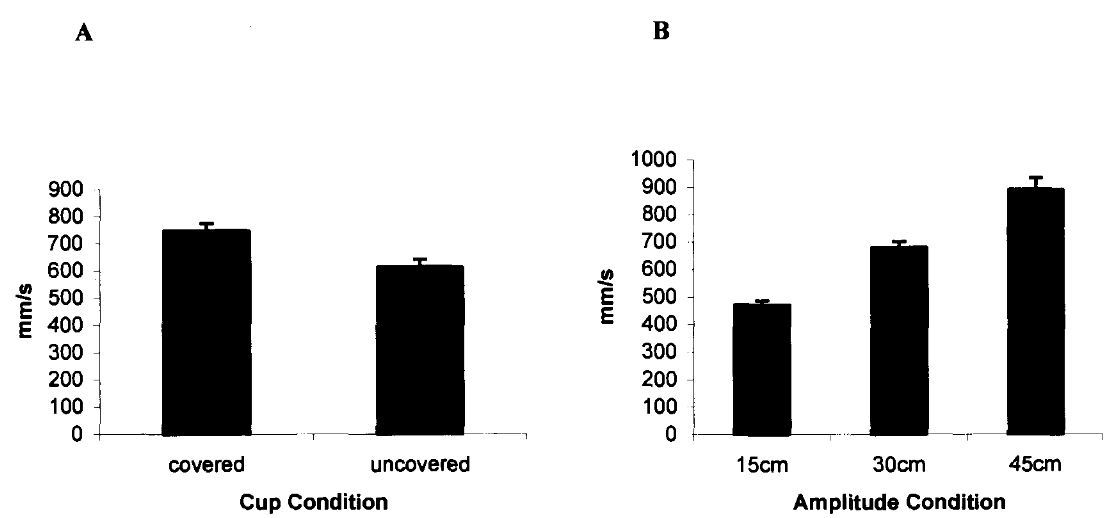
3.3.1.2 Transport Phase

A significant movement time main effect for the cup condition was observed ($F_{1,12}$=77.43, p<.001), in that subjects took longer to transport an uncovered cup as compared to covered cups (see Figure 3.4A). As would be expected, movement times also increased as the amplitude of movement increased (see Figure 3.4B).



Figures 3.4A and 3.4B: A) Mean movement times (with standard errors) for transporting covered versus uncovered cups. B) Mean movement times (with standard errors) as a function of movement amplitude.

The effects for movement time were mirrored by the peak velocities, in that significant cup ($F_{1,12}$=60.26, p<.001) and amplitude ($F_{2,24}$=163.56, p<.001) main effects were found. Subjects reached greater peak velocities when transporting covered versus uncovered cups (Figure 3.5A) and when transporting cups as the amplitude of movement increased (Figure 3.5B)



Figures 3.5A and 3.5B: A) Mean peak velocities (with standard errors) for covered versus uncovered cups. B) Mean peak velocities (with standard errors) as a function of movement amplitude.

In terms of percent time after peak velocity, again it was found that there was a strong trend towards a cup X amplitude interaction ($F_{2,24}$=3.40, p=.05). Although slightly out the range of statistical significance, Figure 3.6 reveals several interesting effects. The first point of interest is that when the cup was uncovered, there were no differences in terms of time spent in deceleration. However when the cup was covered, there was a significant decrease in the time spent in deceleration at the 45cm amplitude as compared to the 15cm and 30cm amplitudes.

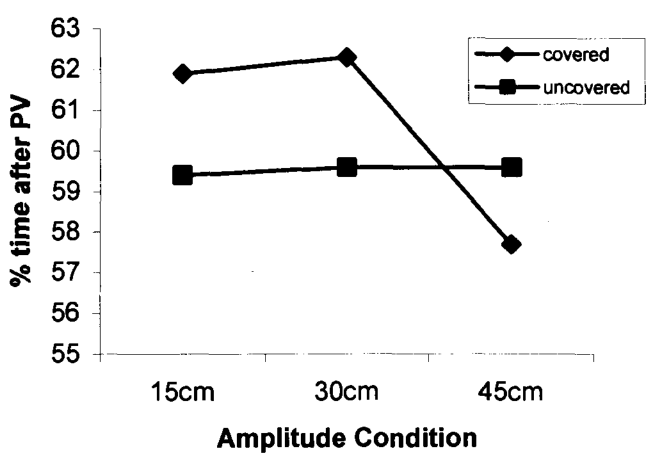


Figure 3.6: Percent time after peak velocity for the wrist during cup transport.

3.3.2 Locomotion Analyses

In order to comprehensively describe the characteristics of gait that were observed in Experiment 1, the results have been divided into separate descriptive and quantitative sections. This division was necessary for several reasons. First, because subjects in Experiment 1 were not given specific instruction on how to structure their walking strategies, it seemed likely that there may be considerable variability both within and between subjects across the various experimental conditions. Our hope was that a descriptive analysis might point to both expected and unexpected trends in the data, as well as identify issues for subsequent inferential analyses. Furthermore, because Experiment 3 of this dissertation proposes a similar locomotion/prehension task, we felt that having a detailed baseline description of these types of data would prove beneficial for comparison purposes as this work unfolds.

3.3.2.1 Descriptive Gait Analysis

In Experiment 1, subjects picked up a cup of water that was either covered or uncovered, transported it to a target, and placed it on that target while walking alongside a table. The target that the cup was to be placed upon was located at one of three positions (15cm, 30cm, or 45cm) directly in front of the cup's starting position. Of primary concern was the pattern of footfalls leading up to and during the course of the prehension task. Specifically, we were first interested in looking at which foot was in stance phase when the cup was lifted from the starting platform with the preferred, right hand.. As it turned out, a discernable pattern was difficult to infer. Starting with the most general overview, it was found that across all conditions, the left foot was in stance phase 61% of the time, while the right foot was down 39% of the time at the time of cup lift.

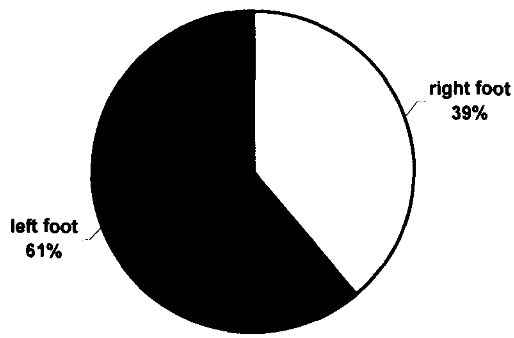


Figure 3.7: Pie chart depicting the overall percentages of which foot was in stance phase at the time of cup lift.

It should be noted, however, that this trend was by no means consistent across all subjects. In fact, five of the thirteen subjects actually used a right-foot-down at cup lift strategy more often than left. The overall trend toward left-foot-down is actually due to the fact that three of the subjects adopted that strategy over 80% of the time (Table 3.1). In fact, if the first three subjects are not considered, the breakdown of right foot to left foot becomes nearly even (48% and 52 %, respectively). For the most part, subjects 4 - 13 did not show any particular tendency toward one foot or the other.

Table 3.1: Gait data of each subject (collapsed across the three amplitude and two cup conditions) in terms of which foot entered into a stance phase just prior to cup lift. The data given are in percentages.

subject	Right foot (%)	Left foot(%)
1	7	93
2	5	95
3	13	87
4	72	28
5	42	58
6	28	72
7	55	45
8	30	70
9	58	42
10	62	38
11	30	70
12	47	53
13	55	45
AVERAGE	**39**	**61**

Another important consideration is that these percentages were determined by observing which foot made the last heelstrike prior to cup lift. However, closer visual inspection of the data revealed that oftentimes the contralateral foot was still in contact with the ground at cup lift. Essentially then, cup lift was often completed with both feet in contact with the ground (see Table 3.2).

Table 3.2: Percentages of two-foot cup lifts by individual subjects

Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	Mean
Percent	20	5	28	28	22	27	28	43	35	53	47	45	52	33

Here again however, there were no clear trends in terms of a two-foot strategy for cup lift. Figure 3.8A shows that the choice to adopt a two-footed stance at cup lift had little to do with whether or not the cup was covered or uncovered. At the 15cm amplitude, there were more two-footed cup lifts when the cup was covered (58) than when it was uncovered (47). Conversely for the 30cm amplitudes, only 27 two-footed lifts were observed for covered cup compared to 59 when the cup was uncovered. A final note regarding two-foot cup lifts is that out of the total of 780 trials that were analyzed, two-footed cup lifts were seen 256 times, or 32.8 percent of the time.

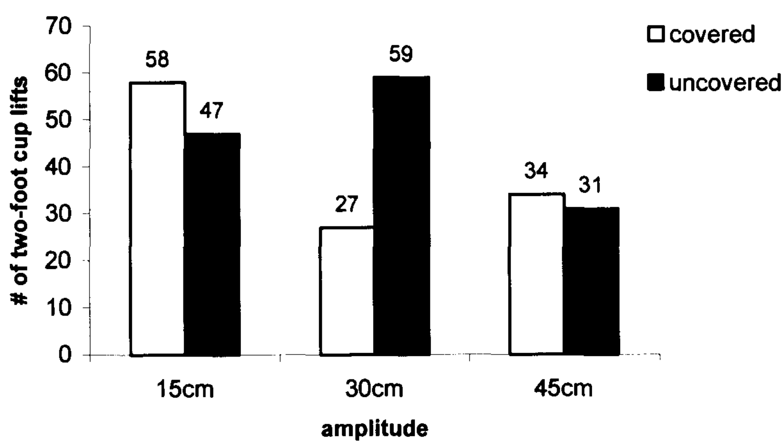


Figure 3.8: The number of times both feet were in contact with the ground at the time of cup lift as a function of cup condition and movement amplitude.

Breaking down the percentages of right or left foot preference by amplitude condition did little in terms of pointing to a particular pattern or strategy. For example, in the 15cm amplitude condition, subject 2 adopted a left-foot-down strategy 98% of the time, regardless of whether or not the cup was covered. Subject 10 on the other hand, had their right foot down at cup lift 98% of the time for this same condition. Also of interest was the finding that within a particular subject, there was a great deal of variability when the trials were separated into covered versus uncovered cup conditions. Although certain subjects did appear to be inclined toward a particular stance strategy for certain conditions, that trend was by no means reliable.

A final important issue to consider is in regard to the gait pattern between cup lift and cup replace as a function of movement amplitude. For the 15cm amplitude, subjects consistently replaced the cup during the stance phase of the stride immediately following the cup lift. In other words, if the cup were picked up while the right foot was in stance phase, the cup would be replaced at the target location during the next stance phase of the left foot. However, for the 30cm and 45cm movements, there were occasions on which subjects would take more than one stride between cup lift and cup replace. This issue raises a statistical concern that will be discussed in the following section.

3.3.2.2 Quantitative Gait Analyses

Due to the aforementioned inconsistencies in the 30cm and 45cm amplitude conditions, particularly between the landmark times of cup lift and cup replace, the gait analyses that follow are concerned only with the 15cm prehensile movement. The primary motivation behind the decision to use only the 15cm amplitude movements in the statistical analyses was the relatively consistent gait pattern between the cup lift and cup replace for the 15cm amplitude movements. More specifically, the trials that were included in the statistical analyses were those that showed only one stride (or half of a complete gait cycle) between cup lift and cup replace. As noted previously, often for the 30cm and 45cm amplitudes, more than one step was taken between cup lift and cup replace. This finding introduces a confounding variable and makes inferences regarding those movements potentially misleading. For this reason, the only practical comparisons were those involving the 15cm amplitude condition.

Another important note is that although there was not a good deal of consistency regarding which foot was down at the time of cup lift, a preliminary comparison showed that left foot stance times at cup lift did not significantly differ from right foot stance times at cup lift. Therefore, there would appear to be regularity in key gait characteristics regardless of which foot happened to be down at the time of cup lift. This point helps to reinforce the decision to use the 15 amplitude movements in the analyses that follows.

A 2 Cup (covered; uncovered) X 2 Foot (ipsilateral; contralateral) X 2 Phase (swing; stance) X 2 Time (pre; post) repeated measures ANOVA was initially run to obtain a measure of the pooled variance of our sample. Simple main effects contrasts using the pooled variance (of the 4-way interaction) were then conducted on the contrasts of interest. A Bonferonni correction (.05) was also employed to protect against the accumulation of familywise error. Ten contrasts in total were conducted which meant our alpha level was set a priori at .005.

To determine whether or not performing a prehensile movement while walking affected the gait pattern, stance times of the strides preceding cup lift (covered) were compared to stance times at the time of cup lift. Figure 3.9A shows that indeed, a significantly greater time was spent in the stance phase during cup lift than in the strides leading up to cup lift $t_{(.005;\,12)}= 4.97$. Similarly, stance times at the time of cup replacement were also significantly longer than were those in the stride prior to cup replacement $t_{(.005;\,12)} = 4.80$ (Figure 3.9B).

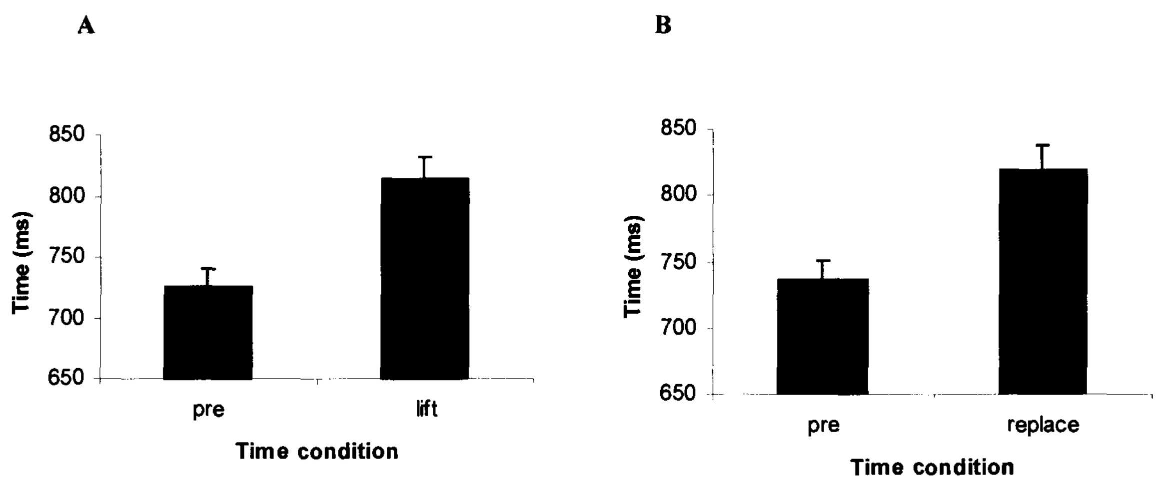
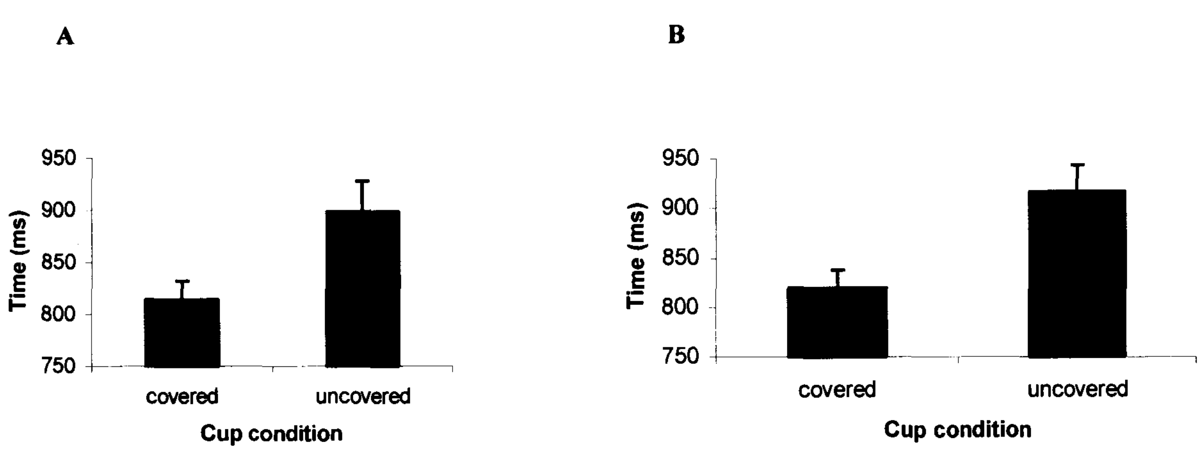


Figure 3.9A and 3.9B: A) A comparison of time spent in stance phases preceding the prehensile movement (pre) compared to those at the time of cup lift (lift). B) A comparison of time spent in stance phase at cup replace (replace) versus stance phases previous to the prehensile movement (pre). Mean values and standard errors are presented.

Interestingly, there were no significant effects for the swing time measures either at cup lift or cup replace. Therefore, based on the analysis of stance and swing times, it would appear as though combining a prehension task with locomotion task impacts only the time spent in the stance phase of gait.

The next series of comparisons sought to determine if adding complexity to the prehension task would further affect the locomotion system. From the outset however, we wanted to ensure that any differences that were noted reflected compensations made at the points of interest during locomotion, and not a general change in gait strategy. To this end, we first compared stance and swing phases prior to any interaction with either the covered or the uncovered cups. Importantly, no differences were noted for either stance phase or swing phase as a result of approaching an uncovered versus a covered cup. Therefore, it can be confidently noted that any adjustments seen in the locomotion system would in fact be the result of complexity manipulations in the prehension task.

Several landmark events in the task involving the covered cup were compared to analogous events in the uncovered cup condition. The results indicated that removing the lid from the cup led to increases in stance time at the time of cup lift $t_{(.005, 12)} = 4.74$ (Figure 3.10A). Furthermore, it was found that stance times were also significantly increased at the time of cup replace when subjects were transporting uncovered versus covered cup $t_{(.005; 12)} = 5.42$ (Figure 3.10B).



Figures 3.10A and 3.10B: A) A comparison stance of times when lifting a covered versus an uncovered cup. B) A comparison of stance times when replacing a covered versus an uncovered cup. Mean values and standard errors are presented.

Once again however, there were no significant statistical effects for any of the measured swing phases as a result of lifting or replacing uncovered versus covered cups. Therefore, it would appear as though adding complexity to the prehension task impacted only the stance phase of the gait cycle.

3.4 Discussion

The results of Experiment 1 suggested that when subjects were required to grasp a cup of water while walking, it was necessary to alter their gait patterns both at the time of cup lift, and at the time of cup replacement. Furthermore, when the task was made more complex by removing the lid from the cup, the gait adaptations were even more pronounced. The finding that adding complexity to a combined upper and lower limb task resulted in adjustments beyond the upper limb raises an interesting question. Namely, are the upper and lower limbs truly controlled in a hierarchical fashion as suggested by Carnahan et al. (1996), or could there be another explanation? A closer examination of the methodology employed by Carnahan et al. (1996) may hold the answer to this question. Subjects in the Carnahan et al. (1996) experiment were required to pick up one of two objects while walking past a support surface. The two objects in this case were an empty aluminum can or a pencil. Although the dimensions of these two objects differed (6.5 cm in diameter X 12.3 cm in height versus 0.8 cm in diameter X 14.9 cm in height, respectively), it is quite reasonable to assume that any adjustments needed to grasp the smaller object could be made at the level of the hand. In this case, it is likely that there was simply no need to adjust the locomotion kinematics to account for the relatively small difference in object size. On the other hand, the methodology of Bertram et al. (1999), as well that of the current study, employed experimental conditions that differed quite significantly in terms of their task complexity. More specifically, grasping and transporting a full cup of water without a lid is much more difficult than grasping and transporting that same cup of water when covered. Therefore, it could be hypothesized that the recruiting of additional body segments to aid in the successful completion of a task is, at least in part, a function of the difficulty or complexity of that task.

A striking feature of the data presented herein is the tremendous amount of variability in the gait strategies adopted by our subjects throughout the experiment. The qualitative analyses failed to reveal any discernable pattern, either between or within subjects, regarding a preferred gait strategy for completing the task. As was noted earlier, while several subjects adopted a left foot down strategy more often at cup lift, others showed just the opposite tendency. Even those subjects who did show a left foot preference, did not necessarily use that strategy consistently across all conditions. However, despite this highly variable behavior, it was shown consistently that removing the lid from the cup resulted in prolonged stance phases at the time of cup lift and cup replace. It was also shown consistently that swing phases remained unaffected by performing a prehensile movement, regardless of whether the cup was covered or uncovered. A final consistency that was observed in this experiment that should not be understated was the successful completion of the task. In fact on average, it took just

170ms longer to transport an uncovered cup than a covered one. Although this is a statistically significant finding, it nonetheless indicates considerable skill and efficiency on the part of those who took part in this experiment. This last point is of particular interest because it demonstrates how task goals can be achieved despite highly variable means. Furthermore, it shows how the upper and lower limbs are able to work together while making individual compensations to task requirements.

In summary, the results described above suggest that the segments that allow for movements involving both the upper and lower limbs are controlled by task-specific synergies. For example, the finding that removing the lid from the cup (thereby making the task more complex) resulted in enhanced adaptations in the upper and lower limbs suggests that the two systems are capable of making individual, yet complementary adjustments to suit the demands of the task. In effect then, it could be argued that the gait system was incorporated *into* the prehension system in a variable manner when the task required it. This observation raises the question of whether or not these separate movement systems are in fact *controlled* separately. The current work would seem to suggest alternatively that the entire system is controlled as an integrated whole.

Chapter 4: Experiment 2

The effects of incremental increases in task complexity on trunk-assisted prehension.

4.1 Introduction

In day-to-day activities, people are often required to reach for and grasp a large variety of objects. In motor control literature, such activities are categorized under the umbrella of prehension. To date, researchers studying prehension have amassed a considerable body of literature on reaching and grasping tasks, and taken great strides towards an understanding of how the motor control system coordinates the hand and the arm during prehension tasks. Recently however, scientists have begun to recognize that reaching for and grasping objects often involves body segments beyond that of the upper limb. More specifically, it has been shown that the torso plays a significant role in transporting the hand to an object, both during seated reaching (e.g., Tyler and Hassan, 1995) and while walking (Marteniuk and Bertram, 2001).

Although current research on trunk-assisted prehension is by no means extensive, many intriguing results have been reported. In addition, this research has produced some interesting inconsistencies. For example, Saling et al. (1996) suggested that when the torso is required to help transport the arm, the upper limb will make compensations when the size of the to-be-grasped object changes, however the movement of the torso carries on unaffected. In other words, the upper limb was seen to be sensitive to the precision requirements of the task, while the torso was not. However, in a similar experiment, Steenbergen et al. (1995) showed that when subjects reached for a full cup of coffee, subjects used a greater degree of torso flexion than when the cup was empty. Further discrepancies in the literature can be found in discussions of grasp characteristics in trunk-assisted reaching experiments. In an experiment in which subjects were to reach for and grasp a dowel using various combinations of arm and torso movement, Wang and Stelmach (1998) reported no spatial or temporal effects for aperture under any of their experimental conditions. These findings prompted the authors to suggest that trunk-assisted prehension is controlled by a hierarchical synergy system, whereby the grasp and transport components operate via independent synergies that are in turn controlled by a higher level synergy which coordinates certain spatial and temporal factors of the two. Reports elsewhere in the literature, however, have shown that under certain conditions, the grasp component does change in response to certain task constraints. Saling et al. (1996) for example, found statistical differences in percent time to peak aperture when subjects reached for small versus large objects. In addition, Seidler and Stelmach (2000) reported changes in both the magnitude and timing of peak aperture when subjects performed trunk-assisted reaching under various temporal constraints.

In Experiment 2, we again address the issue of motor equivalence. Recalling that motor equivalence is characterized by variable means working toward an invariant end (Lashley, 1930), it is logical to expect that if a task goal remains invariant (i.e., achieving a successful grasp), and the task itself becomes more difficult, then the 'variable means' might very well include the recruiting of additional degrees of freedom to support the movement. Mackey et al. (2000) has shown in an experiment involving varying degrees of task complexity, the torso as well as the upper limb reflected the complexity demands of the prehension task. Specifically, when the hand reached for uncovered cups of water, the torso played a larger role in the movement than when the same cup was covered by a lid. These findings are consistent with the notion that motor equivalence is task-specific in nature, in that compensations at the torso level appeared as the task became more difficult. The previously mentioned empirical inconsistencies could likewise be explained using a similar rationale. In other words, it is possible that the Saling et al. (1996) task conditions of grasping a dowel with a 2.2cm diameter versus a dowel 6.7cm in diameter simply did not differ enough in terms of their degree of task complexity so as to elicit further torso involvement. It could be suggested then, for this relatively simple task, that the motor control system simply had no reason to call upon additional degrees of freedom when the necessary compensations could be made at the level of the upper limb. On the other hand, experiments that have employed task conditions that differ more significantly in terms of their task complexity (see Marteniuk & Bertram, 2001 for review) have revealed the potential for a much more highly developed relationship between the upper limb and the torso. The primary goal of Experiment 2 was to determine the effects of incrementally adding complexity to a prehension task on both the upper limb and the torso. We predicted that the task complexity conditions in the current experiment would affect not only the upper limb, but the torso as well. More specifically, we predicted that the torso would play a larger role in terms of its forward displacement as task complexity increased. Furthermore, we predicted that if the torso displacement was affected by the task complexity, then differences should also be seen in the velocity profiles of the torso. In other words, it is possible that the velocity profiles of the torso could show a precision effect, or a lengthened deceleration phase (see Bootsma, Marteniuk, MacKenzie, & Zaal, 1994 for review).

An additional goal of Experiment 2 was to determine if the qualitative observations of Bertram et al. (2000) regarding spatial variability could be substantiated statistically. These authors reported that the movement of the endpoint to covered cups of water seemed to be generated in a more variable manner than did movements to uncovered cups. If these observations were found to hold true, a possible conclusion that could be drawn from such a suggestion is that prehensile task complexity leads to a tighter management of the relationship between the hand and the torso. Alternatively, should subsequent analyses reveal that endpoint variability is not affected by task complexity, it could be argued that maintaining consistent endpoint movement through space is a higher-order control variable for the human motor system.

In summary, although the central and peripheral mechanisms involved in body-assisted reaching are becoming better understood, this particular area of study is still relatively new, and thus, many questions remain unanswered. For example, how do certain object properties and task complexity constraints affect the coordination between the torso and the upper limb? The current study seeks to answer this question and others by systematically manipulating task complexity and observing the compensatory adaptations made by the motor control system to these altered task demands. Finally, we hope to reconcile some of the previously mentioned discrepancies in the literature, and advance a more unified theory regarding the control of trunk-assisted prehension.

4.2 Methodology

4.2.1 Participants

Fifteen healthy, right-handed adults with normal or corrected-to-normal vision participated in this experiment. All persons gave informed consent prior to the experimental session. Subjects were given a ten-dollar honorarium for their participation in this study. Each experimental session lasted approximately 30 minutes. Ethical approval from the Simon Fraser University Office of the Vice President, Research was obtained prior to beginning the experiment.

4.2.2 Apparatus

An OPTOTRAK (Northern Digital, Waterloo, Canada) 3-dimensional camera system was used to record the motion of 6 infrared emitting diodes (IREDs). Three IREDs were positioned on the subject's hand (lateral styloid process of the wrist, tip of the thumb, tip of the index finger) and the other three IREDs were affixed to a Velcro strap which was attached to the subject's torso. The three torso IREDs were positioned in an L-shaped configuration over the superior portion of the subject's sternum. The position of the IREDs over time was sampled at 200Hz and transferred to a Sun workstation for analysis.

A plastic cup served as the to-be-grasped object in this experiment. The cup measured 8.8 cm in height by 5.5 cm in diameter. The cup had a metal washer affixed to its underside and sat on a metal contact plate (5 cm in diameter) so that when the cup was grasped and lifted, a circuit was broken that served to indicate the end of the trial. This contact break was also sampled at 200 Hz by the OPTOTRAK Data Acquisition Unit

(ODAU) that was controlled by an IBM-PC in conjunction with the OPTOTRAK 3020 camera system.

4.2.3 Procedure

Each subject read and signed an informed consent on the day of their experimental session. Once completed, the subjects were given a few minutes to read over a written set of instructions that outlined the experimental procedure. The subjects were then seated and instrumented with six IREDs. Next, each subject was measured to determine the functional reach of the right hand and arm without any contribution from the torso. This was achieved by asking each subject to first sit with their backs against the back of the chair (Figure 4.1). At that point we asked each subject to reach forward with their right hand as far as was comfortable without leaning forward, and the experimenter then positioned the chair so the tip of the outstretched hand was at the mid-way point between the start and target positions (i.e., 20 cm from the starting position). Standardizing the functional reach of each subject prior to testing was done to ensure that the experimental task necessitated the use of the torso to complete the movement.

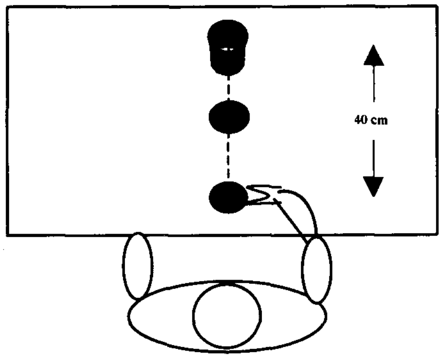


Figure 4.1: Experimental set-up.

The objective of the task for Experiment 2 was to reach for, grasp, and then lift a cup of water that was positioned at a target 40 cm directly in front of the subject's starting position. The to-be-grasped cup was either full of water (approximately 154ml; 86.2g), half full of water (approximately 77ml; 63.5g), or empty (approximately 36.1g). The cup was uncovered in all conditions. Following six practice trials to allow the participants to familiarize themselves with the task, the experimental trials began. Following an auditory "go" signal from the experimenter, the subjects were instructed to reach as quickly and as accurately as possible, and without spilling the water, grasp and lift the cup. Once the cup was grasped, the subject was to lift the cup to height of approximately 10 cm and hold it for approximately two seconds. Each subject performed three blocks (empty; half full; full) of ten trials each. The order of the cup conditions was counterbalanced across all subjects. If any water was spilled on any trial, that trial was redone, and the error was noted.

4.2.4 Data Processing and Analysis

At the completion of each experimental session, all of the data files were transferred from the IBM-PC to a Sun workstation for analysis using customized WATSMART and WATSCOPE software. OPTOTRAK files missing four or less consecutive frames were interpolated, while those files missing more than four consecutive frames within the movement time were discarded. In order to define a meaningful frame of reference, the data were then rotated such that the principal (i.e., forward) axis of movement was defined as the positive x-axis, lateral movement was defined as the y-axis, and the vertical movement was defined as the z-axis. The data were then filtered using a Butterworth dual-pass filter (8Hz) in order to reduce any distortion that may have been picked up in the movement recording process.

The data were interpreted in terms of two frames of reference. First, a traditional world-centered coordinate system was used to describe the body movements in relation to the workspace of the task. It should be noted that according to the world-centered frame of reference, the motion of the wrist (i.e., endpoint) IRED reflected the combined actions of the arm and trunk movement. In order to gain an understanding of the transport characteristics of the arm independent of trunk contributions, the data were also analyzed using the body as a dynamic frame of reference. This was accomplished by subtracting the movement of the one of the torso IREDs from the movement of the wrist IRED at each sample point.

The dependent measures of interest regarding upper limb movement for Experiment 2 were as follows: movement time (MT), peak resultant velocity (PV), time after peak resultant velocity (TaPV), percent time after peak resultant velocity (%TaPV), peak aperture (PKAP), and percent time after peak aperture (%TaPKAP). Movement time of the upper limb was defined as the time from when the wrist IRED exceeded and remained at 10% of its peak velocity value (as the start of movement) to the time of cup lift (as determined by a voltage change at the contact plate). Velocity profiles were obtained by differentiating the OPTOTRAK position data in x, y, and z coordinates via the central finite difference technique. Resultant velocities were then calculated as the square root of the sum of the squared x, y, and z components. Finally, peak velocity (mm/s), and time from peak velocity (ms) were then obtained from these velocity profiles.

Regarding the movement of the torso, we analyzed the displacement of the torso (in mm) in the primary, or x dimension of movement. We also looked at the movement time of the torso, as defined as the time between when the torso velocity exceeded 10% of its peak value, until the time of cuplift. Peak velocity and percent time after peak velocity for the torso were also analyzed.

The trial-to-trial spatial variability of the wrist (endpoint) IRED was determined as follows: filtered data were first time normalized to 100 samples. Next, trials within each condition were averaged and the standard deviations for the x, y, and z dimensions were calculated. The spatial variability of each subject was then calculated by taking the square root of the sum of the variances in each direction. Finally, the within-subject variability in each of the three conditions was averaged across subjects. The resulting variability curves were then analyzed for differences in peak magnitude and percentage of time to peak variability.

Huynh-Feldt epsilon was evaluated to determine whether the repeated measures data met the assumption of sphericity (>.75). Because the sphericity assumption was met for each variable, we used the univariate tests to maintain power.

4.3 Results

The results of Experiment 2 are broken down into the following sections: 1) the upper limb, including a) wrist kinematics (movement time, peak velocity, percent time after peak velocity) and b) aperture (peak aperture, percent time after peak aperture); 2) the torso, including a) chest displacement, and b) chest kinematics (movement time, peak velocity, percent time after peak velocity). Each of the above dependent measures were analyzed using separate one-way 3 Cup (full, half full, empty) repeated measures

ANOVAs. Significant results were then subjected to Tukey's HSD post-hoc analyses (α=.05). In addition, spatial path variability (peak variability; percent time to peak variability) was analyzed using separate 3 Segment (torso, arm, endpoint) x 3 Cup (empty, half full, full) repeated measures ANOVAs. Again, follow up contrasts were made using Tukey's post-hoc procedures.

4.3.1 The Upper Limb

4.3.1.1 Wrist Kinematics

Figure 4.2 depicts the significant cup main effect that was found for movement time, with subjects reaching fastest for the empty cup (825ms), followed by the half full cup (909ms), and finally the full cup (1153ms) ($F_{2,28}$=30.47, p<.001). Post hoc analyses revealed that the empty cup and half full cup conditions were faster than the full cup condition, but the empty and half full conditions were not significantly different.

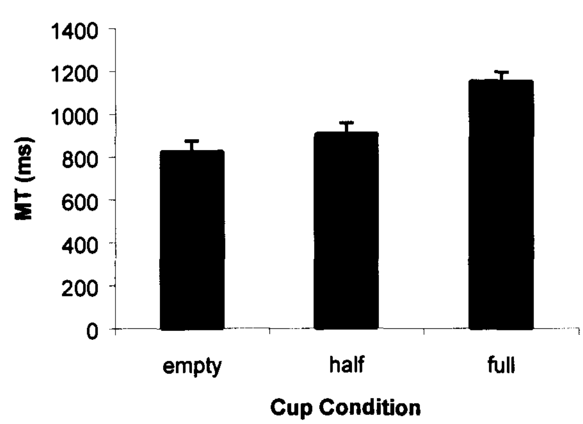


Figure 4.2: Movement time of the wrist as a function of task complexity. Mean values and standard errors are presented.

As would be expected, results for peak velocity mirrored the movement time effects with the greatest peak velocities observed for reaches to empty cups (163mm/s), followed by the half full condition (156mm/s), and the empty cup condition (135mm/s) ($F_{2,28}$=3.70, p=.037). Again, Tukey's test determined that the empty cup and half full cup conditions were faster than the full cup condition, but the peak velocities for the empty and half full conditions were not statistically different.

A precision effect (Marteniuk et al., 1987) was also noted for the upper limb, in that a greater percentage of time was spent decelerating when subjects reached for full cups, versus half full and empty cups ($F_{2,28}$=23.30, p<.001) (Figure 4.3).

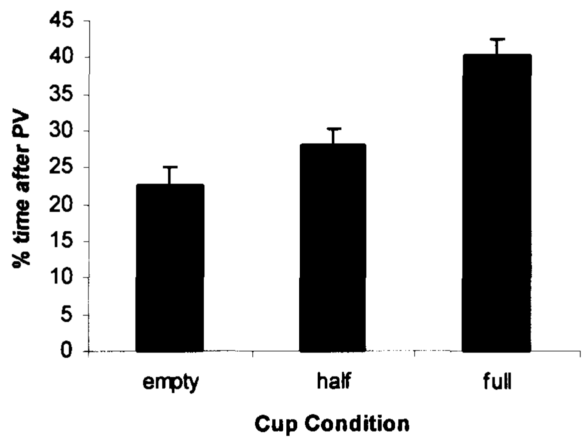


Figure 4.3: Percent time after peak velocity of the wrist as a function of task complexity. Mean values and standard errors are presented.

Consistent with movement time and peak velocity findings, post hoc tests showed that all differences except for that between the empty and half full cup conditions were significantly different.

4.3.1.2 Aperture

Peak aperture data revealed no significant difference among the cup conditions ($F_{2,28}$=2.12, p=.139), indicating that the contents of the cup had little bearing on the width of the grasp aperture. However, Figure 4.4 shows that when subjects were reaching to grasp full cup, a greater percentage of time was spent after peak aperture versus half full or empty cups ($F=_{2,28}=56.5$, $p<001$). Tukey's test confirmed that each of the three cup conditions were significantly different from the others.

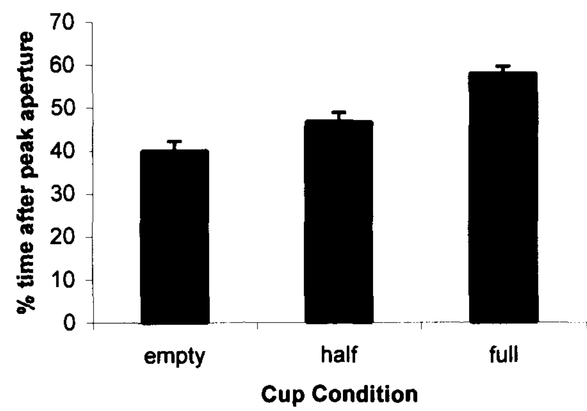


Figure 4.4: Percent time after peak aperture as a function of task complexity. Mean values and standard errors are presented.

4.3.2 The Torso

4.3.2.1 Chest Displacement

For Experiment 2, subjects needed to lean forward at the torso in order to reach the to-be-grasped cups. Figure 4.5 reveals that significantly more torso flexion was utilized when subjects reached for cups containing water versus empty cups ($F_{2,28}=15.41$, $p<.001$). More specifically, although the differences between the empty cup and half full conditions did not reach significance, torso movement in the empty (129mm) and half full cup (137mm) conditions was less than the full cup condition (150mm).

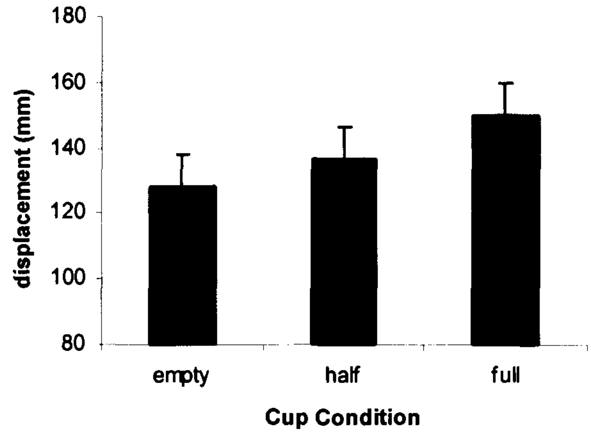


Figure 4.5: Chest displacement as a function of task complexity. Mean values and standard errors are presented.

4.3.2.2 Torso Kinematics

Movement times for the torso were found to be significantly longer for reaches to full cups (1190ms) versus half full (907ms) and empty cups (838ms) ($F_{2,28}$=23.74, p<.001). Interestingly, Figure 4.6 shows that the torso was also sensitive to the precision requirements of the task, in that a greater percentage of time after peak velocity was observed for the full cup condition versus the half full and empty cup conditions ($F_{2,28}$=48.41, p<.001).

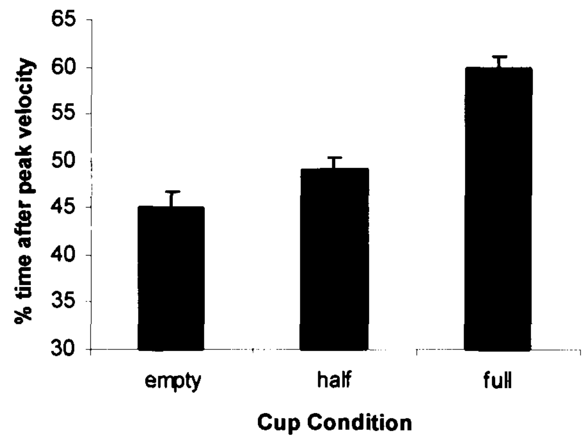
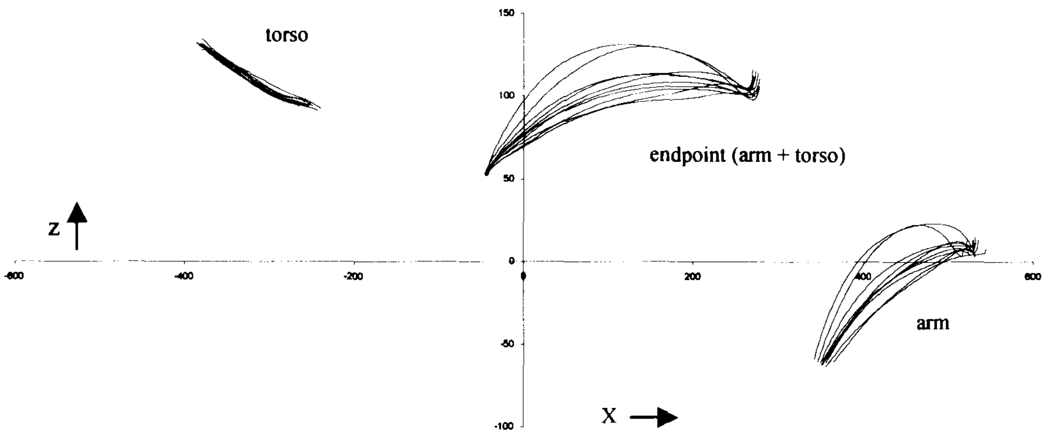


Figure 4.6: Percentage of time spent in deceleration for the torso as a function of task complexity. Mean values and standard errors are presented.

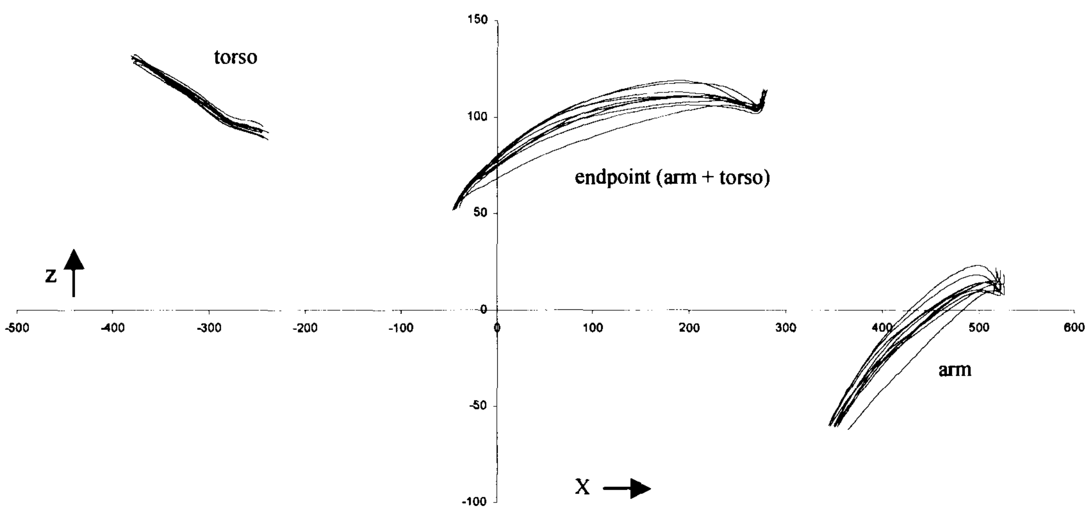
4.3.3 Spatial Path Variability

Figures 4.7 A, B, and C show the two-dimensional spatial path plots for a representative subject for each experimental condition. These plots represent the horizontal (x) and vertical (z) displacement of a representative subject. Each graph contains three plots: 1) torso displacement, 2) endpoint displacement, and 3) arm displacement (endpoint minus torso).

A


torso
endpoint (arm + torso)
arm
z
x
150
100
50
0
-50
-100
-600
-400
-200
200
400
600

B


torso
endpoint (arm + torso)
arm
z
x
150
100
50
0
-50
-100
-500
-400
-300
-200
-100
0
100
200
300
400
500
600

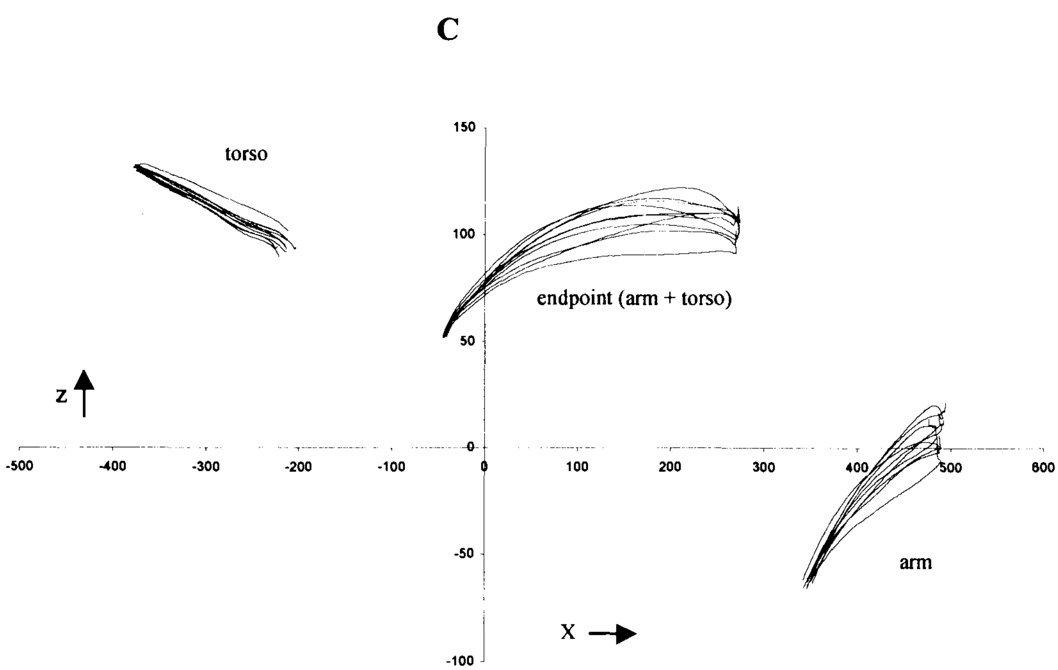


Figure 4.7: Spatial path plots of the horizontal (x) and vertical (z) displacement of the wrist and chest for one subject during: A) Empty cup condition, B) Half full cup condition C) Full cup condition

Each of the three plots within each graph represents the same ten trials for that particular condition. In each graph, the torso is seen to be moving in the negative z direction as it moves forward in the x dimension, indicating that as the body leans forward to assist with the reach, it also arcs downward. The endpoint movement in each graph, which is comprised of contributions from the arm and the torso, moves in the positive z direction as it begins to move forward, reaches its maximum in vertical space, and then starts to decrease in the z dimension as the end of movement approaches. This arc is essentially a trace of the wrist marker as it left the starting position at the beginning of the movement until the cup was lifted. The slight vertical spikes at the end of the individual trials show that the wrist had begun to move upward before contact had been broken between the cup and the contact plate. Finally, the arm displacement plots depict the net movement of the arm, which was determined by calculating the difference between the endpoint and the torso. In effect then, these plots represent the movement of the arm alone during the reach to grasp, without any contribution from the body.

By observing the graphs in Figure 4.7, one can get some idea of the trial-to-trial variability, within each condition of each of the movement segments. We were interested to see if and how this within-condition variability changed across all of our subjects. It is important to note that the graphs in Figure 4.7 depict movement in only two dimensions. However, because participants in this study were actually free to move in three dimensions, all measures as they pertain to variability have taken into account possible movement (and hence spatial variability) in each of the x, y, and z dimensions.

The graph in Figure 4.8 represents the mean three-dimensional spatial path variability for the endpoint (i.e., arm + torso) for each of the three experimental conditions. The figure shows that in each condition, the spatial variability of the endpoint is unimodal, starting at a minimum value, increasing consistently as the reach to grasp movement began to unfold, and then progressively decreasing as the subject prepared to grasp the cup.

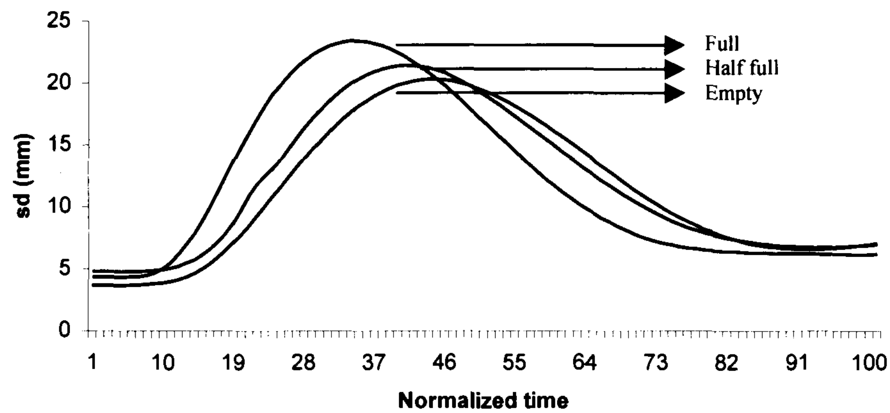


Figure 4.8: Mean normalized endpoint variability as a function of task complexity.

Although the peak values for spatial variability of the individual cup conditions appear at first glance to be different, the repeated measures ANOVA failed to reach significance ($F_{2,28}$=1.45, p=.251). Interestingly however, when we looked at the percentage of time to the peak variability, a significant main effect for the cup condition was revealed ($F_{2,28}$=9.77, p=.001). Figure 4.8 shows that when subjects were reaching for an empty cup, the peak spatial variability was reached significantly later than when the cup was half full or full. Post-hoc contrasts indicated that the empty cup condition was significantly different than the full cup condition; however, neither the differences between the half full and full conditions, nor those between the empty and half full conditions managed to achieve statistical significance.

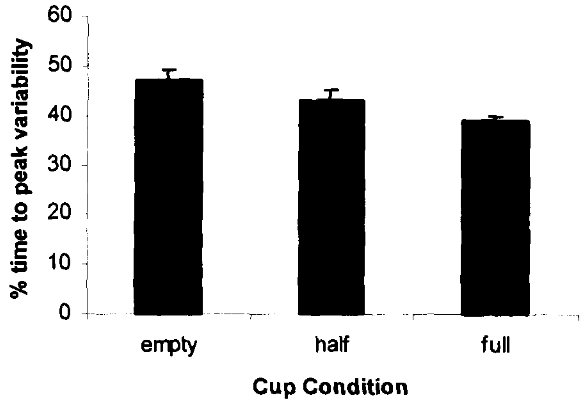
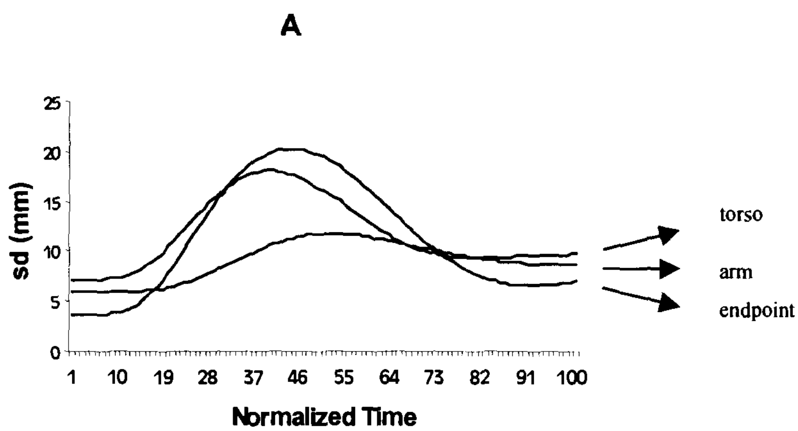
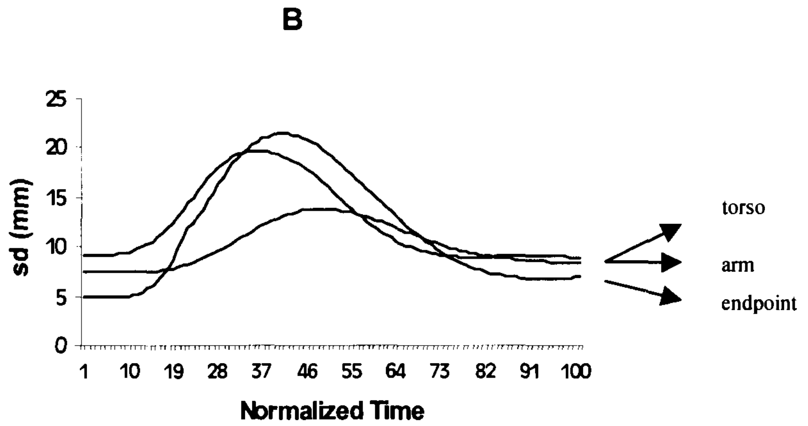


Figure 4.9: Percent time to peak variability as a function of task complexity. Mean values and standard errors are presented.

We were also interested to see how the spatial variability of the individual segments (i.e., the torso, endpoint, arm alone) changed as task complexity increased. Figures 4.10 A, B, and C depict the variability of the segments in each of the empty, half full and full cup conditions. The pattern of variability was similar in all three conditions, in that at approximately 75% of the way through the movement, the variability of the endpoint became, and stayed below either the arm alone or the torso.





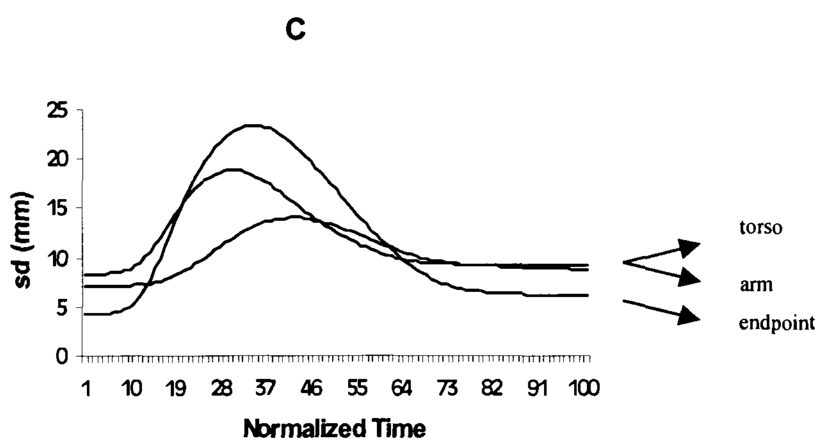


Figure 4.10: Variability plots of the endpoint, arm, and torso segments across normalized time. A) Segment variability for reaching to grasp an empty cup; B) Segment variability for reaching to grasp a half full cup; C) Segment variability for reaching to grasp a full cup

4.4 Discussion

Executing reaching and grasping movements to objects that are beyond the reach of the arm creates an interesting problem for the motor control system. Instead of having just to coordinate the musculature of the arm and the hand, a situation arises in the trunk must be activated, and blended into the overall motor activity. This new unit of coordination, or synergy, that is generated must now take into account the torso's role in the transport of the arm, and must therefore mediate compensatory actions in the upper limb. The fact that the motor control system is able to select from an infinite variety of possible combinations of degrees of freedom, and consistently generate graceful arm trajectories, is truly a remarkable thing.

Ma and Feldman (1995) first advanced the idea that the redundancy issue involved in trunk-assisted reaching could be solved, at least partially, by a combination of two functionally different synergies: one which involves only the arm joints to transport the hand to an object, and one that coordinates the trunk and the upper limb to allow the hand movements to carry on seemingly unaffected. Our results support this idea in that relatively smooth endpoint spatial trajectories were observed under differing complexity conditions that saw the torso playing an increasingly greater role in the overall movement (Figures 4.7 A, B, and C). Other reports in the literature (e.g., Pigeon & Feldman, 1998; Saling et al., 1996) have likewise supported this claim, and the existence of a mechanism which allows for coordinated trade-offs between the upper limb and the torso seems well documented.

Wang and Stelmach (1998) added to the coordination issue by recognizing that a third synergy, one that is responsible for grasp formation, must also be factored in to the planning and execution of these complex prehensile actions. These authors found that neither the spatial nor the temporal grasp measures were affected when subjects reached for a dowel using the arm only, the trunk only, or a combination of the two. However, the transport components of the movement, which involved aspects of the arm and/or the trunk, were altered depending on the reach strategy that was imposed. Based on these discoveries, Wang and Stelmach (1998) proposed that the synergy responsible for the grasp formation operates independent of the transport synergy, thereby allowing the grasp kinematics to remain invariant. In contradiction to the Wang and Stelmach (1998) findings, our results showed that as task complexity increased, a greater percentage of time was spent after peak aperture (Figure 4.4). Therefore, it would appear that the grasping action can in fact compensate along with the arm and the torso under certain conditions. Similar findings have been reported elsewhere in the literature (Seidler & Stelmach, 2001; Saling et al., 1996)

Another interesting and somewhat contradictory finding that comes out of the current study is the extent to which the torso was affected by the addition of task complexity. A previous study by Saling et al. (1996) reported that when subjects were to reach for and grasp large or small dowels placed beyond arm's reach, the torso kinematics were unaffected by the change in dowel size. Our results suggest otherwise. More specifically, our findings showed that not only did the torso play a greater role in the movement when task complexity increased, but further, its velocity profile displayed a lengthened deceleration phase for the full cup condition (Figure 4.6). Based on these findings and the aforementioned grasp adaptations, it would seem that the circumstances of the task dictate when and where compensations occur, not a rigid hierarchy of control.

Also at issue in this experiment was the notion of spatial variability. At the outset, we predicted that if the torso was shown to play a more significant role in more complex reaching movements, the result might be a decrease in the amount of spatial variability that was exhibited at the endpoint. It turned out this was not the case. Instead, we reported that there were in fact no differences in the peak variability between the conditions. Although this result was unexpected, it is nonetheless an intriguing finding. Despite the fact that adding complexity to the prehension task vastly altered the execution of the prehensile action, it did not seem to affect the magnitude of the endpoint variability between conditions. While all other elements of the movement, from the grasp, to the transport, to the role of the torso were affected by additional complexity, variability was not. Based on this outcome, it is possible that the maintaining of a consistent endpoint trajectory through space could be an important control variable for the motor control system. In fact, such a suggestion is in keeping with endpoint control theory (see Rosenbaum, 1991 for review).

It is also interesting to note that the time after peak spatial variability was similar to the results for time after peak velocity. More specifically, reaching for a full cup of water resulted in both the peak velocity and peak variability being reached earlier in the movement. One possible interpretation of this finding is that the spatial variability is associated with the speed of the movement. Perhaps this should not be surprising given that speed has been shown time and again to trade off with accuracy; however, variability in terminal accuracy is not necessarily synonymous with variability along a spatial trajectory. Furthermore, even if speed is related to the variability between trials in terms of the time after peak, the fact remains that the magnitude of the peak variability did not differ between conditions. Peak velocity, on the other hand, was influenced by task complexity. We recognize that firm conclusions regarding spatial variability and its role as a control variable are difficult to draw at this point; however, we feel the current results warrant a call for further investigation of this issue.

Our results have also nicely demonstrated that motor equivalence plays a strong role in trunk-assisted prehension actions. First, we showed that the upper limb and the torso both reflected the incremental increases in task complexity. The torso in particular, was shown not only to contribute more in terms of its overall movement, but was also able to compensate for more complex conditions by adjusting its kinematic profile. These adjustments at the torso level therefore meant that the control system had to make compensations to the movement of the upper limb in order to counteract the torso and keep the hand on a steady course toward the to-be-grasped cup. Given that our task employed only one movement amplitude, it is logical to conclude that if the torso contributed more (under certain task conditions) to the transport of the endpoint to the object, then the role of the arm, in terms of its flexion at the shoulder joint and extension at the elbow joint must therefore decrease. We did not measure joint angles in this experiment, but these intuitive assertions have been documented previously in the literature (Steenbergen et al., 1995). Therefore, it is suggested that when the trunk component of the movement is increased, the extent to which its movement must be coupled with the arm to preserve the required coordination of the prehensile act must also be increased.

The finding that peak variability did not change across complexity conditions could likewise be considered as evidence for motor equivalence. Bearing in mind that motor equivalence is reflected in a variable means working toward an invariant end, it is interesting to note that even though numerous features of the movement were sensitive to the imposed complexity constraints, peak variability was not. It could very well be that one of the ways an "invariant end" (i.e., a smooth endpoint trajectory and a successful grasp) is achieved by controlling the level of variability at the endpoint.

In summary, the results of the current study indicate that the motor control system is able to organize independent neuromuscular synergies into a single, *functional* synergy whose characteristics depend on the demands of the task. We suggest further that is by way of this task-driven synergy that multiple, redundant degrees of freedom can be controlled in an efficient, goal-oriented manner.

Chapter 5: Experiment 3

The effects of incremental increases in task complexity: A further investigation into multi-segmental coordination in a prehension task involving locomotion.

5.1 Introduction

The seemingly effortless act of reaching for and grasping an object involves the highly specialized interaction between the larger, proximal muscle groups that move the arm through space and the smaller, more distal muscles that shape the hand for the grasp. If the to-be-grasped object happens to be located at some distance from the body, a situation arises in which a person may have to lean forward at the waist to increase his range of motion. Or perhaps that person might even have to walk towards the object, and grasp it on the move. In either of these last two scenarios, the motor control system has the added burden of having to summon additional support for the transport of the hand, while simultaneously having to issue commands to the hand to counteract the movement the these additional segments. In the case of grasping objects while walking, the hand must actually compensate not only for the forward progress of the body, but also for the raising and lowering that accompanies locomotion, the possible lateral movement of the body, and angular movements about the waist that may be generated to help align the body with the object prior to grasp.

Together then, the results of Experiments 1 and 2 have suggested that although two or more of the body's motor systems (e.g. prehension system, locomotion system) often work independently of one another, they can in fact work as a single integrated system when the demands of the task require it. The third experiment of this dissertation sought to combine the ideas expressed in the first two experiments, and to build upon those ideas in light of a new series of results. In Experiment 1, the primary goal was to investigate if and how gait patterns are affected when simultaneously performing a prehensile activity. The results of Experiment 1 showed clearly that the locomotion system contributed to the successful grasp and transport of a cup of water. In turn, the upper limb was able to compensate for the changing contribution of the gait system by consistently achieving a successful grasp.

Having demonstrated that upper limb tasks can be assisted by lower limb adjustments, the next high-level goal of this work was to gain a clearer understanding of the coordination between the upper and lower limbs. Given that the torso provides an anatomical and functional link between the two systems, we determined that a logical way to begin an examination of such a complex movement synergy would be to first investigate how the upper limb and the torso worked together during seated prehension. Once the coordination of these two movement segments was better understood, we hoped to later (i.e., in Experiment 3) be able to determine how reintroducing locomotion would affect the performance of the task. Moreover, because there is a larger theory base in the literature regarding trunk-assisted prehension movements, it was thought that expanding this theory into the relatively unique, but related area of body-assisted prehension (or combined locomotion/prehension) would serve our goals well. Thus, in Experiment 2, a trunk-assisted reaching task was designed to investigate how incrementally adding complexity to a reaching and grasping activity affected the coordination between the upper limb and the torso. The results of Experiment 2 showed the torso was able to enhance its role in transporting the hand to the object when task complexity increased, both in terms of it overall displacement and its kinematic profile. Furthermore, the hand was able to compensate for the altered means of transportation, and consistently achieved a successful grasp.

The purpose then, for Experiment 3, was fourfold. First, we wished to reaffirm the results of Experiment 1 and show that characteristics of the gait pattern are affected by the complexity of the upper limb task. Towards that end, a one-way 3 Cup (empty; half full; full) task was designed. As in Experiment 2, task complexity was manipulated by altering the amount of water that was in a to-be-grasped cup. In the current experiment however, subjects had to perform the task while walking. We predicted, based on the results of Experiment 1, that gait patterns, specifically the time spent in stance phase, would reflect the incremental increases in task complexity.

The second purpose of Experiment 3 was to determine how performing a prehension task while walking would affect the coordination between the upper limb and the body. Based on the results of Experiment 2, we predicted that the torso would play a varying role in the transport of the hand under the different conditions of task complexity. More specifically, it was predicted that when the task called for grasping a full cup of water, adjustments would be seen in the overall displacement of the torso, the kinematic profile of the torso, and in the amount of angular rotation of the torso.

The third purpose of Experiment 3 was to observe the movement of the upper limb both in isolation, and in relation to the moving body across the conditions of complexity. If the prehensile task was to be consistently and successfully achieved, ultimately the upper limb would need to be compensating for the varying contributions of the gait system and the torso to the overall movement. Evidence for such compensations should be seen in both the kinematic profiles of the upper limb movement, as well as in the spatial path trajectories of the upper limb throughout the task.

A fourth and final purpose for Experiment 3 was to demonstrate how motor equivalence arises in response to increases in task complexity. As in Experiment 2, it was predicted that if the task goal (i.e., successful grasp) remained invariant, and the task itself became more difficult, than the *variable means* to the invariant end could include the recruiting of additional degrees of freedom. The results of Experiments 1 and 2 have supported this claim, and further evidence was predicted for the present work. In other words, we predicted that our data would show each of the involved motor segments working together as a single functional unit to ensure successful task completion.

A final prediction for Experiment 3 is regarding spatial variability and how it relates to the topic of motor equivalence. In Experiment 2, we looked at how the three-dimensional spatial variability of the endpoint (i.e., the combination of the arm and body movement) changed across the conditions of task complexity. The results showed that the magnitude of the peak variability did not increase as task complexity increased. While unexpected, this result raised the question of whether or not endpoint variability could be an important control variable for the motor system. On the basis of this finding, we predicted in the present experiment that the magnitude of the peak endpoint variability would not differ across the levels of complexity during the reach to grasp portion of this combined walking and prehension task. Furthermore, if endpoint variability is being controlled, we should also see evidence that the variability of the component parts of the prehensile action (the arm and the torso) is greater than that of the endpoint. Seidler & Stelmach (2001) provided evidence for such trends in variability using a trunk-assisted reaching task. Likewise, the results of Experiment 2 also speak to this issue. Experiment 3 looked to expand upon this work within the context of a combined prehension/locomotion task.

5.2 Methodology

5.2.1 Participants

Twelve Simon Fraser University undergraduates participated in this experiment. All subjects were right-handed and had normal or corrected-to-normal vision. Prior to the experimental session, all subjects completed and signed informed consent forms and read an information sheet that provided a brief overview and explanation of the experiment. All participants received a $10 honorarium for taking part in the experiment. Ethical approval from the Simon Fraser Office of the Vice President, Research was obtained prior to beginning the experiment.

5.2.2 Apparatus

Three dimensional position data were collected (at 200 Hz) using an OPTOTRAK 3020 3-dimensional camera system (Northern Digital, Waterloo, Ontario) that was controlled by an IBM-PC. The OPTOTRAK recorded the movement of seven infrared emitting diodes (IREDs) that were affixed to strategic anatomical landmarks on each subject. Three IREDs were placed on the subjects chest (aligned L-shaped over the sternum), three more were placed at the belt level of each subject (inferior to the chest IREDs; configured in an L-shape down the mid-line), and one final IRED was affixed to the radial styloid process of each subject's right wrist. The torso IREDs were fastened to two separate elastic straps, one that was secured around the chest, and the other around the waist.

The to-be-grasped object for Experiment 3 consisted of a plastic cup that was either empty (approximately 36.1g), half full of water (approximately 77ml; 63.5g), or full of water (approximately 154ml; 86.2g). The cup measured 8.6cm high, 5.5cm in diameter around the top, and 4.5cm in diameter at the bottom. A 120cm x 75cm x 75cm table was used as the working surface for this task. Two height-adjustable laboratory jacks were clamped to the table and spaced 15cm apart to serve as surfaces for the starting position and target position of the cup. Metal washers (5cm in diameter) were attached to the underside of the cup and to the surface of the laboratory jacks so that the lifting of the cup could be determined by voltage changes. These voltage changes were recorded at 200 Hz by the OTOTRAK Data Acquisition Unit (ODAU) that was controlled by an IBM-PC in conjunction with the OPTOTRAK camera system.

Subjects were also instrumented with a set of footswitches (B&L Engineering) that were placed into a pair of slippers and worn by the subjects throughout the course of the experimental session. As each subject walked during a given trial, the pressure generated during a stance phase of locomotion resulted in the closing of a switch. When the foot was lifted during toe-off and went into a swing phase, the switch was then opened and a change in voltage was registered. The time from heelstrike to ipsilateral toe-off was considered one stance phase. Conversely, the time between toe-off and ipsilateral heelstrike was measured to be a single swing phase.

5.2.3 Procedure

In general, the task for Experiment 3 was to walk approximately 2.5m to a table that was placed parallel to the walking path (on the subject's right), pick up a cup of water, transport that cup to a target, place the cup on the target, then continue walking for approximately 1.5 m. For one third of the trials, the cup was completely filled with water. The remaining two thirds of the trials consisted of having the cup either half filled with water or completely empty. The cup conditions were blocked and their order of presentation was counterbalanced. Each block consisted of ten trials per condition.

Upon arrival to the laboratory, each participant was asked to read and sign an informed consent form and to take a few minutes to review a written set of instructions. If there were no questions or concerns, each participant was then instrumented with the seven IREDs and the footswitches. Once subjects were instrumented and tested to ensure all equipment was working properly, each subject's height was standardized to the working space of the task. This was be achieved by having each subject stand and grasp the cup at its starting position. The height of the laboratory jacks was then adjusted until the participant's right arm was flexed to 90 degrees while holding the cup. Subjects were asked to grasp the cup near its top edge so that the wrist IRED would remain in view of the camera throughout each trial. Once the subjects were comfortable moving in the apparatus, they were led to the starting position for the experiment.

Following an auditory "go" signal from an experimenter, the subjects were asked to begin walking forward and alongside the experimental table. As they continued walking past the table, the subjects were to reach for, grasp, and transport the cup 15cm from the starting position to the target position. Finally, the subjects were to set the cup down on the target location and continue walking for approximately 1.5 m. The total walking distance was approximately 5m. Each subject was instructed to walk at a comfortable pace throughout each trial, and to transport the cup from start to target as quickly and as accurately as possible without spilling any of the water. If any water was spilled on any trial, that trial was redone, and the error was noted.

The above methodology yielded a one-way, 3 Cup (empty; half full; full) condition, within-subjects design. Ten trials were performed in each condition in a blocked manner. Prior to starting each new block, subjects were given two practice trials in that condition. Thus, each subject performed a total of thirty experimental trials and six practice trials. Testing time was approximately one hour.

5.2.4 Data Processing and Analysis

At the completion of each experimental session, all of the data files were transferred from the IBM-PC to a Sun workstation for analysis using WATSMART and WATSCOPE programs. OPTOTRAK files missing four or less consecutive frames were interpolated, while those files missing more than four consecutive frames within the movement time were discarded. In order to define a meaningful frame of reference, the data were then rotated such that the principal (i.e., forward) axis of movement was defined as the positive x-axis, lateral movement was defined as the y-axis, and the vertical movement was denoted as the z-axis. The data were then filtered using a Butterworth dual-pass filter at 8Hz in order to reduce any distortion that may have been picked up in the movement recording process.

Because the task consisted of two phases, a reach-to-grasp (approach) phase and a transport phase, the analyses were divided accordingly. As in Experiment 1, the approach phase was defined as 200 frames of data (or one second prior to cuplift) until the cup was lifted. Because the time at which the IREDs first became visible to the camera differed from trial to trial and subject to subject, the data underwent a preliminary visual inspection to determine a standardized start point for all subjects. Next, the transport phase was defined as the time from when the cup was lifted until it was replaced on the target position.

The upper limb data were interpreted in terms of two frames of reference. First, a traditional world-centered coordinate system was used which described body movements in relation to the workspace of the task during both the approach and transport phases of the movement. The data were also analyzed using the body as a dynamic frame of reference. This was accomplished by subtracting the movement of one of the chest IREDs from the movement of the wrist IRED, thereby allowing us to observe the motion of the wrist independent of the contribution of the torso and lower limbs.

Regarding the approach phase, the dependent measures of interest regarding upper limb movement were peak approach velocity (PV), and time after peak velocity (TaPV) of the wrist. Regarding the transport phase, the dependent measures of interest were: Movement (MT), peak transport velocity (PV), time after peak transport velocity (TaPV), and percent time after peak transport velocity (%TaPV). Transport time was defined as the time from cup lift to the time of cup replace, as determined by voltage changes at the contact plates. Velocity profiles were obtained by differentiating the OPTOTRAK position data in x, y, and z coordinates via the central finite difference technique. Resultant velocities were calculated using each of the x, y, and z components. Finally, peak velocity (ms), and time from peak velocity (ms) were obtained from these velocity profiles.

The movement of the torso was also analyzed both in terms of its forward displacement (mm) during the approach and transport phases, as well as its angular rotation during the prehension task. Torso angles were calculated by comparing the movement of a rigid body constructed from the three chest IREDs against the three waist IREDs. The 0,0,0 (x, y, and z respectively) position for the angular calculations was achieved when subjects stood directly in front of the OPTOTRAK camera. As the subject turned at the waist to manipulate the cup, the result was rotation (yaw) about the z- or vertical axis. We compared the amount of rotation that occurred during both the approach phase and the transport phase of the task.

Several comparisons of gait characteristics were also analyzed. First, a comparison of stance times leading up to cup lift was analyzed for each condition to examine whether or not subjects were using a consistent gait pattern prior to cup lift. Second, of particular interest were the differences in gait that result from adding of complexity to the prehension task. Specifically, the following comparisons were analyzed: 1) stance times (ms) at the point of cup lift versus the stance phase prior to interacting with the empty, half full, or full cup; 2) stance phases (ms) at cup replace versus the stance phase prior to setting down either the empty, half full, or full cup; 3) stance and swing phases (ms) at cup lift and replace across the three complexity conditions of empty, half full, and full cup.

The trial-to-trial spatial variability of the wrist and torso IREDs was determined as follows: first, filtered data were time normalized to 100 samples. Next, trials within each condition were averaged and the standard deviations for the x, y, and z dimensions were calculated. The spatial variability of each subject was then calculated by taking the square root of the sum of the variances in each direction. Finally, the within-subject variability in each of the three conditions was averaged across subjects.

Huynh-Feldt epsilon was evaluated to determine whether the repeated measures data met the assumption of sphericity (>.75). Because the sphericity assumption was met for each variable, the univariate tests were used to maintain power.

5.3 Results

The prehension task in Experiment 3 required participants to first reach for and grasp a cup of water, and then to transport that cup of water to a target position while walking. In essence then, the upper limb task was twofold and hence calls for two separate analyses: one for the approach phase and one for the transport phase. The first set of analyses (approach) deals with the movement characteristics of the upper limb during the final 200 frames, or 1 second of data collected just prior to cup lift. The second series of analyses deals with the transport phase, or the time between when the cup was lifted and when it was placed upon the target.

Following a thorough kinematic description of the upper limb movement, we report the results of the torso movement, both in terms of its overall displacement before and during cup lift, as well as its angular changes throughout the task. The third major section of this chapter deals with the analysis of gait characteristics. In this section, the time spent in both the stance and swing phases of locomotion are reported at key times during the prehension movement. Moreover, we report the effects of adding complexity to the upper limb task on the patterns of locomotion. The final section of this chapter is concerned with spatial path variability. Here, horizontal and vertical displacement plots of the upper limb and torso are displayed graphically along with an analysis of the variability within those plots during both the approach and transport phases of the task.

5.3.1 The Upper Limb

5.3.1.1 Approach phase

Figure 5.1 shows that peak velocity values for the wrist IRED were significantly lower in the full cup condition (1490mm/s) than for either the half full (2051mm/s) or empty cup (2044mm/s) conditions ($F_{2,22}$=26.07, p<.001). In other words, during the final second or 200 frames before cup lift, the peak velocity of the endpoint was lower when subjects reached for a full cup of water. Tukey's tests confirmed that reaches to the full cup were significantly slower than were reaches to either the half full of empty cup, which did not significantly differ from each other.

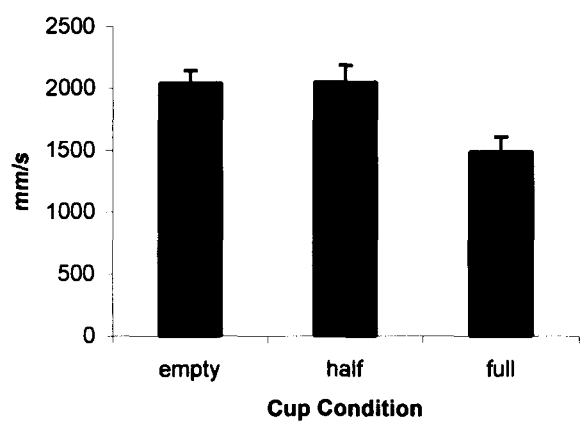


Figure 5.1: Peak approach velocity of the upper limb. Mean values and standard errors are shown.

Time after peak velocity during the approach phase was also found to be statistically significant ($F_{2,22}$=11.96, p<.001), with a longer deceleration phase being noted in the full cup condition versus the half full or empty cup conditions. The half full and empty cup conditions did not differ statistically.

5.3.1.2 Transport phase

Once the subjects achieved a grasp on the cup, they were then required to move the cup forward 15cm from the starting position to a target location. Within this time period, a significant main effect was found for movement time when task complexity was increased ($F_{2,22}$=106.29, p<.001). More specifically, subjects were fastest when transporting empty cups (343ms), followed by half full cups (419ms), and full cups (610ms) (Figure 5.2). Post-hoc contrasts revealed that each of the movement times significantly differed from the others.

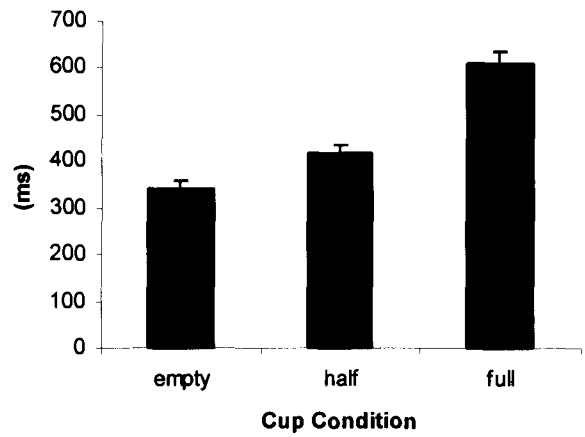


Figure 5.2: Movement time of the wrist during cup transport. Mean values and standard errors are shown.

As might be expected, the results for peak velocity during the transport phase (Figure 5.3) mirrored the movement time results, with the highest peak velocities observed in the empty cup condition (553mm/s), followed by the half full cup condition (488mm/s) and the full cup condition (403mm/s) ($F_{2,22}$=80.74, p<001). Again, each of the three conditions of task complexity was found to be significantly different than the others.

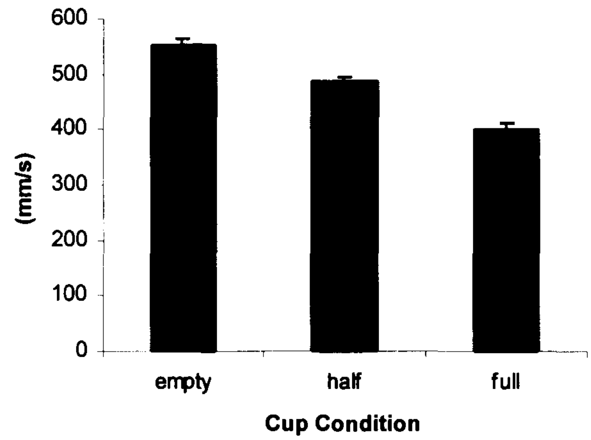


Figure 5.3: Peak velocity of the wrist during cup transport. Mean values and standard errors are shown.

Because of the significant main effect for movement time, we chose to look at deceleration time as a percentage of the overall movement time, as opposed to an absolute measure of time after peak velocity. Using this time-normalized data, it was found that subjects spent relatively more time decelerating when transporting full cups of water to a target position than when the cup was half full or empty ($F_{2,22}$=5.73, p=.01). Post-hoc contrasts revealed that all three cup conditions significantly differed from the others (Figure 5.4). Interestingly, this result indicates the presence of a precision effect for the transporting of an object from one position to another. Traditionally, precision effects (e.g. Marteniuk et al., 1987; Bootsma et al., 1994) are observed during the reach to grasp portion of the movement. Whether or not a transporting movement is analogous to a reach to grasp movement in terms of its velocity profile is not clear, but it is certainly an area open to further investigation.

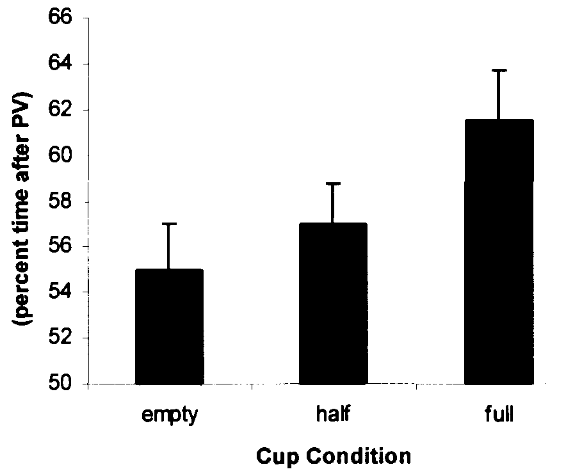


Figure 5.4: Percent time after peak velocity for the wrist during cup transport. Mean values and standard errors are shown.

5.3.2 The Torso

Figure 5.5 shows a significant main effect for torso displacement during the approach phase of movement ($F_{2,22}$=39.85, p<.001). Furthermore, post-hoc contrasts showed that the torso moved further in the forward (x) dimension of movement when the cup was empty or half full than when it was full. The empty and half full cup conditions did not differ significantly from one another. Because these movements occurred in the same one second time frame, these results imply that the torso was moving faster when approaching an empty or half full cup versus a full cup.

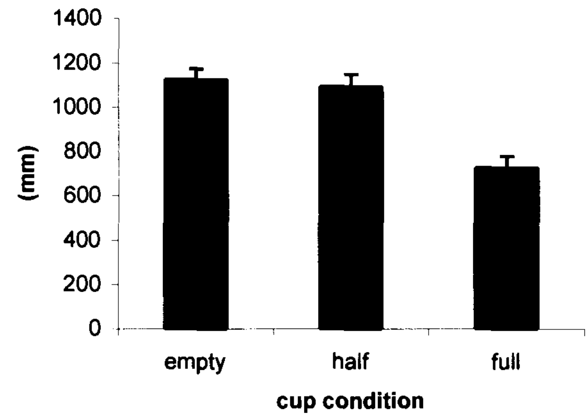


Figure 5.5: Torso displacement during approach. Mean values and standard errors are shown.

Angular movement of the torso was also found to be significant during the approach phase, both in terms of rotation about the z-axis (yaw) ($F_{2,22}$=12.75, p<.001), and flexion about the y-axis (pitch) (($F_{2,22}$=6.48, p=.006). In other words, in the last second prior to cup lift, subjects tended to lean forward at the waist, and turn their torsos toward the cup. Post hoc analyses revealed that in both cases, reaching for a full cup resulted in greater angular torso involvement versus either the half full or empty cup conditions (Figures 5.6A and B). The empty cup and half full cup conditions did not statistically differ from each other.

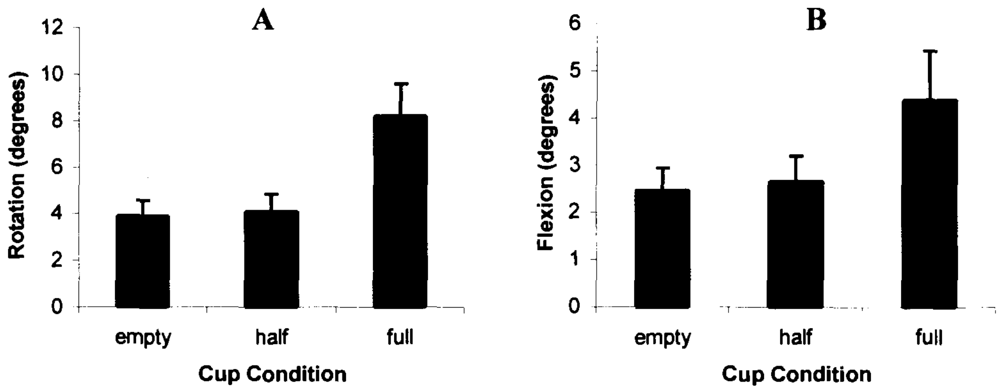


Figure 5.6: Angular movement of the torso during approach. A: Rotation (yaw) about the z-axis, B: Flexion (pitch) about the y-axis. Mean values and standard errors are shown.

Regarding the transport phase, a significant cup condition main effect was found for torso displacement ($F_{2,22}$=7.38, p=.004). Tukey's tests indicated that the torso moved less when transporting an empty cup versus a half full or full cup, which did not differ from each other (Figure 5.7).

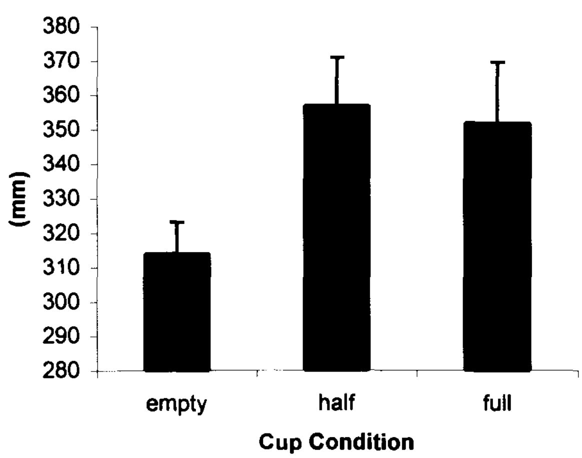


Figure 5.7: Torso displacement during cup transport. Mean values and standard errors are shown.

Interestingly, the results for torso displacement during cup transport were quite different from those during approach. During approach for example, the torso moved further when the cup was empty than when it was full; however, once the cup was grasped and was being transported, the results were just the opposite. Combined, these findings suggest that when the cup was empty, the torso moved closer to the cup before it was grasped (implying less arm movement). Therefore, the arm played a greater role in transporting the empty cup to the target. However, when the cup was full, the torso played a smaller role in the reach to grasp portion of the movement, and a greater role during cup transport. Another interpretation here is that the arm plays a greater role in reaching to grasp full cups, and a lesser role in their transport.

The torso displacement results for the half full condition occupied an interesting middle ground. During the approach phase, the half full condition was statistically equivalent to the empty cup condition, while during transport, it mirrored the full cup condition.

A final note regarding the movement of the torso is that the angular measures of rotation and flexion/extension failed to reach statistical significance for the transport phase of the prehension movement. In other words, once the cup was grasped, no further angular adjustments were made during the transport of cup, suggesting that placing the cup on the target position was controlled by the upper limb and/or the gait system.

5.3.3 Locomotion Analyses

The instructions given to the subjects in Experiment 3 regarding gait were very similar to those in Experiment 1, which is to say there were very few. Aside from being told to walk at a comfortable pace and to continue walking throughout the trial, subjects were free to start walking with whichever foot they wanted, and generally carry out a gait pattern of their own choosing. For that reason, in Experiment 1, we chose to describe the general patterns used by the individual subjects and the group as a whole. In Experiment 1 it was found that subjects employed a left foot down at cup lift strategy 61% of the time. In the current experiment, this trend increased, with subjects using a left foot down strategy at cup lift 78% of the time (Table 5.1).

subject	Right foot (%)	Left foot(%)
1	10	90
2	3	97
3	33	77
4	33	67
5	13	87
6	43	57
7	10	90
8	20	80
9	63	37
10	33	67
11	10	90
12	7	93
AVERAGE	**22**	**78**

Table 5.1: Gait data for each individual subject in terms of which foot had entered into stance phase just prior to cup lift. The data are in percentages.

Considering in both experiments, the to-be-grasped object was on the right side of the subject, this finding was logical. Carnahan et al. (1996) noted that when walking is combined with reaching, the discrete reach is superimposed upon the normal swing of the arms during locomotion. It would make sense then, that if the right arm was performing the reach to grasp, and the reach was being superimposed on the normal arm swing, then the contralateral (i.e., the left) foot should be going into stance phase. For the majority of the trials in Experiment 3, this was in fact the case.

As in Experiment 1, we were again interested in comparing the time spent in various stance and swing phases throughout the task. To do so, a 3 Cup (empty; half full; full) x 2 Foot (ipsilateral; contralateral) x 2 Time (pre; post) x 2 Phase (swing; stance) repeated measures ANOVA was run to obtain a measure of the pooled variance of the sample. Simple main effect comparisons were then conducted using dependent T-tests (α=.05) on the comparisons of interest. To protect against the inflation of familywise error, the T-tests were adjusted using the Bonferonni correction method (.05). Ten contrasts in total were conducted which meant our alpha level was set a priori at .005.

The first comparisons of interest involved the differences between stance times at cup lift versus the stance times of the stride preceding any interaction with the cup for the three levels of task complexity. First, when the task involved grasping and transporting an empty cup, the difference between the time spent in the stance phase before cup lift and the stance time during cup lift was not statistically significant ($t_{(22)}$=0.87). Likewise, in the half full cup condition, the differences in stance time before and during cup lift were not found to be statistically significant ($t_{(22)}$=2.34). However, when the task was to grasp and transport a full cup (Figure 5.8), it was found that the stance phase during cup lift (870ms) was significantly longer than the stance phase preceding cup lift (688) ($t_{(22)}$=3.13, $p<.005$). In other words, the gait system only made significant adjustments during the most complex task condition.

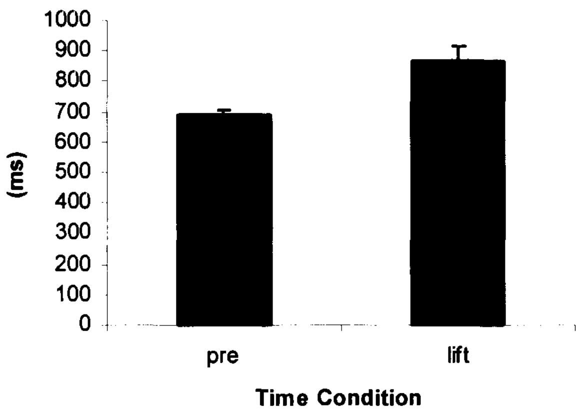


Figure 5.8: Stance times for the full cup condition. The x-axis depicts stance phases for strides proceeding cup lift (pre) and during cup lift (lift). The time in milliseconds is shown on the y-axis. Mean values and standard errors are shown.

Next, we compared stance phases at the time of cup replace versus stance phases prior to interaction with the cup. Although no differences were found between these two stance phases for either the empty cup ($t_{(22)}$=0.98) or half full cup ($t_{(22)}$=2.53), the stance phase at the time of cup replace was significantly longer than strides preceding cup replace for the full cup condition ($t_{(22)}$=3.05, $p<.005$) (Figure 5.9). Again, only during the most complex task conditions was the gait pattern adjusted.

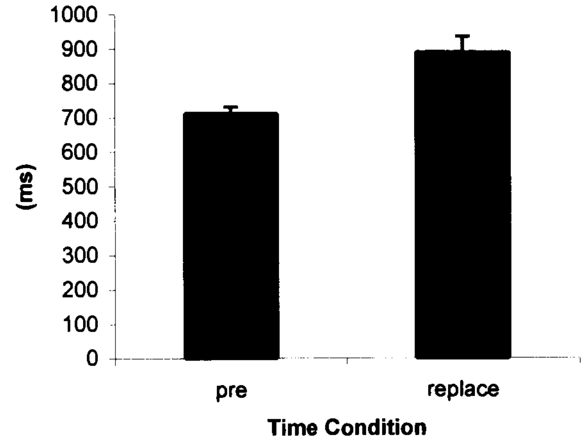


Figure 5.9: Stance times for the full cup condition. The x-axis depicts stance phases for strides preceding cup replace (pre) and during cup replace (replace). The time in milliseconds is shown on the y-axis. Mean values and standard errors are shown.

To determine whether or not stance phases at the time of cup lift and cup replace differed as a function of task complexity, separate one-way 3 Cup (empty; half full; full) ANOVAs were run on the gait data. The results (Figure 5.10) showed a significant cup main effect for time spent in stance phase at cup lift. Post-hoc contrasts revealed that a significantly greater time was spent in stance phase at the time of cup lift when the cup was full (870ms), than when it was half full (795ms) or empty (716ms) ($F_{2,22}$=7.63, p=.003).

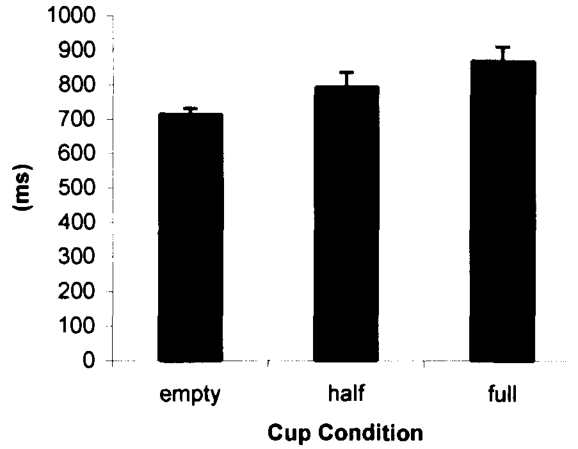


Figure 5.10: Stance times at cup lift as a function of task complexity. Mean values and standard errors are shown.

Similarly, a comparison of the stance phases at the time of cup replace showed stance times increased as task complexity increased ($F_{2,22}$=10.61, p=.001). More specifically, Figure 5.11 reveals that stance times at cup replace were longest when the cup was full (889ms), followed by the half full (816ms) and empty cup (721ms) conditions. Tukey's tests showed that each of the means significantly differed from the others.

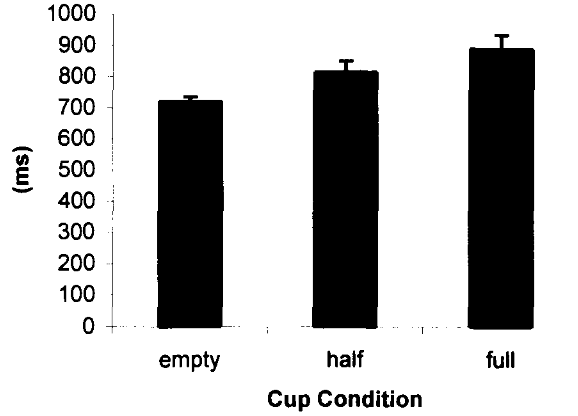


Figure 5.11: Stance times at cup replace as a function of task complexity. Mean values and standard errors are shown.

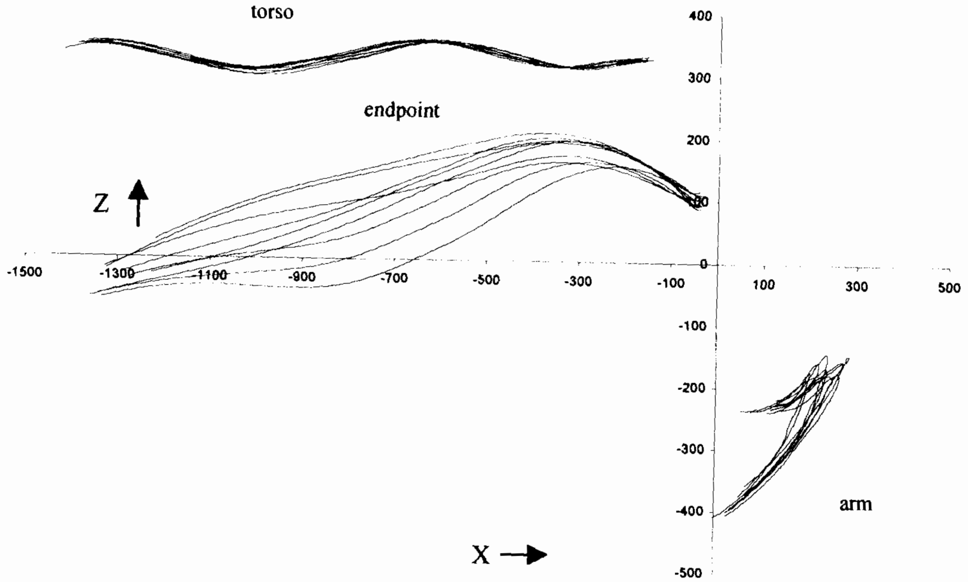
A final note regarding the gait patterns observed in Experiment 3 is that comparisons of swing phases throughout the task failed to reach statistical significance. These results are consistent with those reported in Experiment 1 and those reported elsewhere in the literature (e.g., Carnahan et al., 1996).

5.3.4 Spatial Path Plots

5.3.4.1 Approach

Figures 5.12 A, B, and C show the two-dimensional spatial path plots for each of the three experimental conditions for the approach phase of the task. The plots each represent the horizontal (x) and vertical (z) displacement for a representative subject. Each figure contains three plots: 1) torso displacement, 2) endpoint (arm + torso) displacement, and 3) arm displacement.

A


torso
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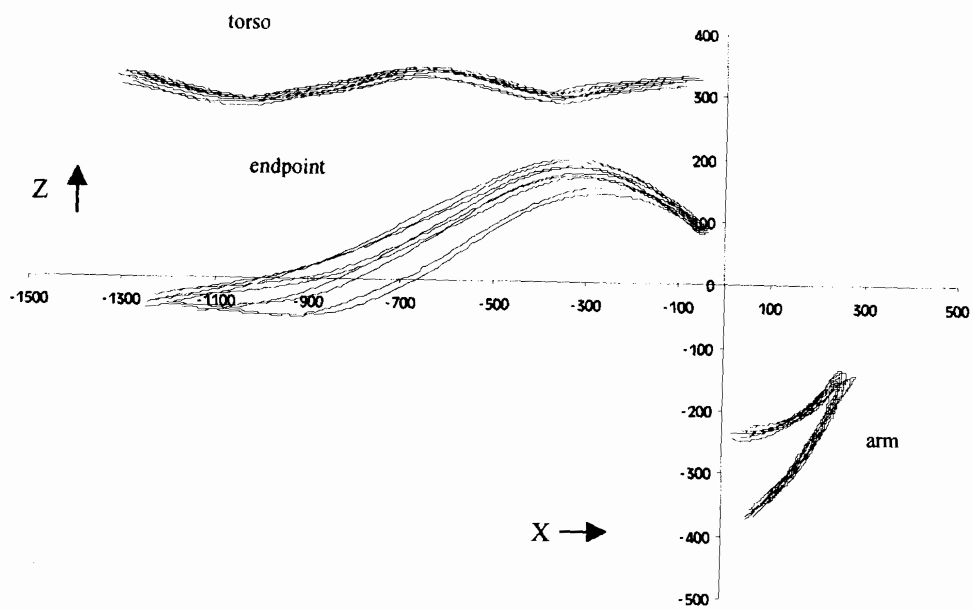
B


torso
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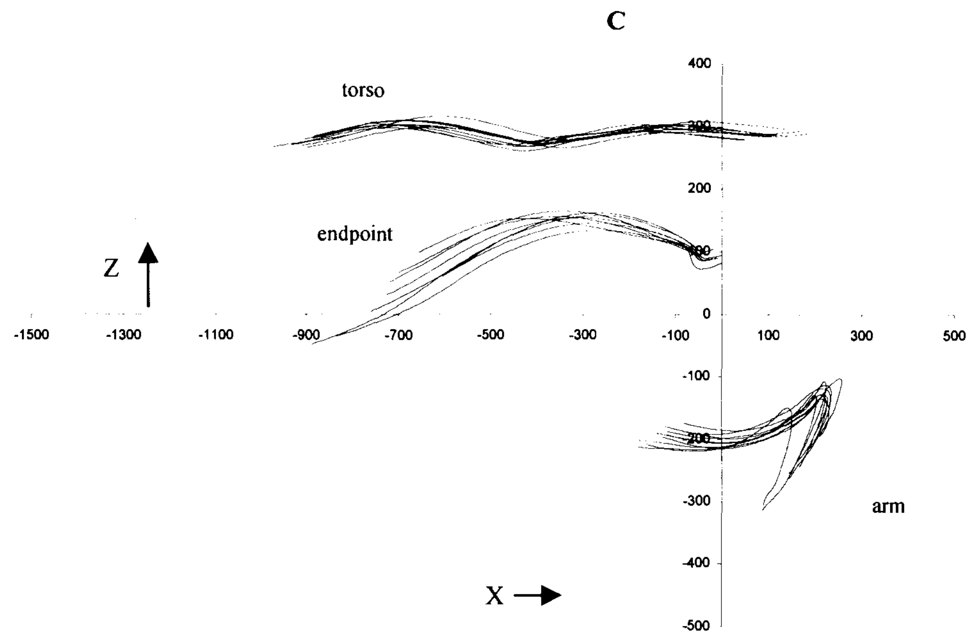


Figure 5.12: Spatial path plots (depicting the horizontal (x) and vertical (z) displacement) for the torso, endpoint, and arm alone during the approach phase for a single subject. A: Empty cup condition, B: Half full cup condition, C: Full cup condition.

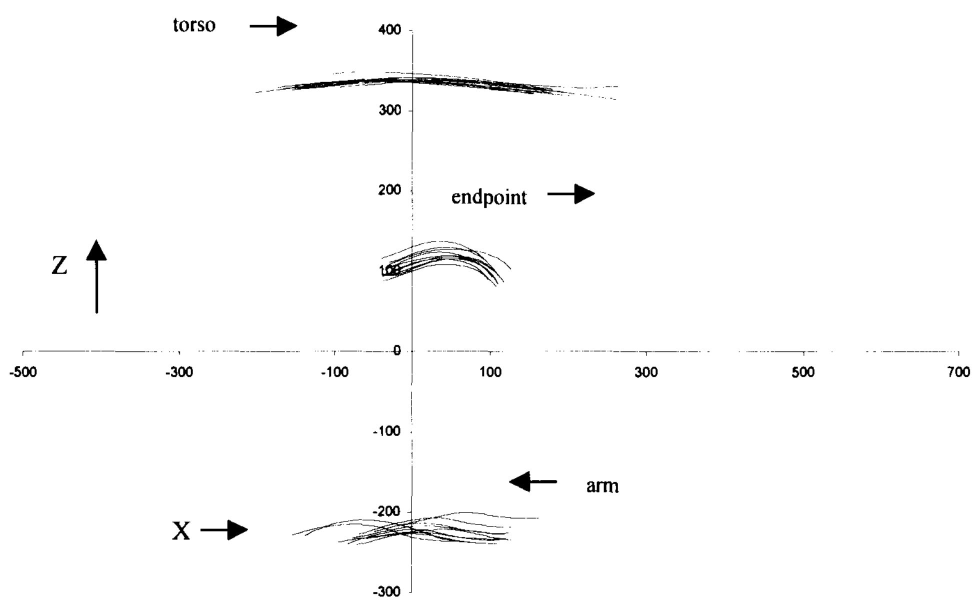
Each of the three plots within each figure represent the same ten trials for that particular condition. In each graph, the torso is seen to be moving up and down in the z direction as it moves forward in the positive x direction. These movements show how the torso rises and falls as the subject walked to pick up the cup. The endpoint plots in each graph, which are comprised of movements of the moving torso plus the arm, moved in the positive z direction for the first portion of the movement, reached a maximum in vertical space, and then started to decrease in the z direction as the hand neared the moment of grasp. These series of arcs are essentially a trace of the wrist marker throughout the second just prior to cup lift, and show how the reach is superimposed on the natural arm swing during locomotion. Finally, the arm displacement plots depict the net movement of the arm, which was determined by calculating the difference between the endpoint and the torso. In effect then, these plots represent the movement of the arm without any contribution from the moving body. It is interesting to note the that in each of the three arm displacement plots, the movement of the arm began at a minimum point in the z dimension, then began to increase in the z dimension as it increased in the x dimension, then rather abruptly reversed and moved in the negative x direction. This reversal is the net-effect of the forward movement of torso taking over the arm's role in endpoint transport.

Another point of interest is how the general shape of the plots within each figure changed as task complexity is increased. Consider first the torso plots in each of the three figures. Looking at Figure 5.12A, note how the lines representing the torso displacement end before crossing the ordinate axis in the empty condition. The ordinate axis is approximately where the cup was located, and therefore, in the empty cup condition, the cup was grasped before the body had caught up to the hand. By comparison, in the full cup condition (5.12C), the lines representing the torso cross over the ordinate axis, and therefore the torso had passed the hand when the cup was grasped. Presumably this correction was made to allow the hand to be nearer to the body, thus creating a more stable posture for the grasping of the full cup. Similar findings have been reported elsewhere in trunk-assisted prehension (Steenbergen et al., 1995) and combined locomotion/aiming (Marteniuk et al., 2000) experiments.

5.3.4.2 Transport

Figures 5.13A, B, and C depict a continuation of the spatial plots for the same representative subject; however, in these graphs, the hand had already grasped the cup and was transporting it from the start position to the target position. Note that again, each figure contains the plots of ten trials for each experimental condition. The lines nearest the top in each figure represent the torso displacement, the middles lines are the endpoint (arm + torso), and the lower lines in each figure represent the displacement of the arm alone.

A



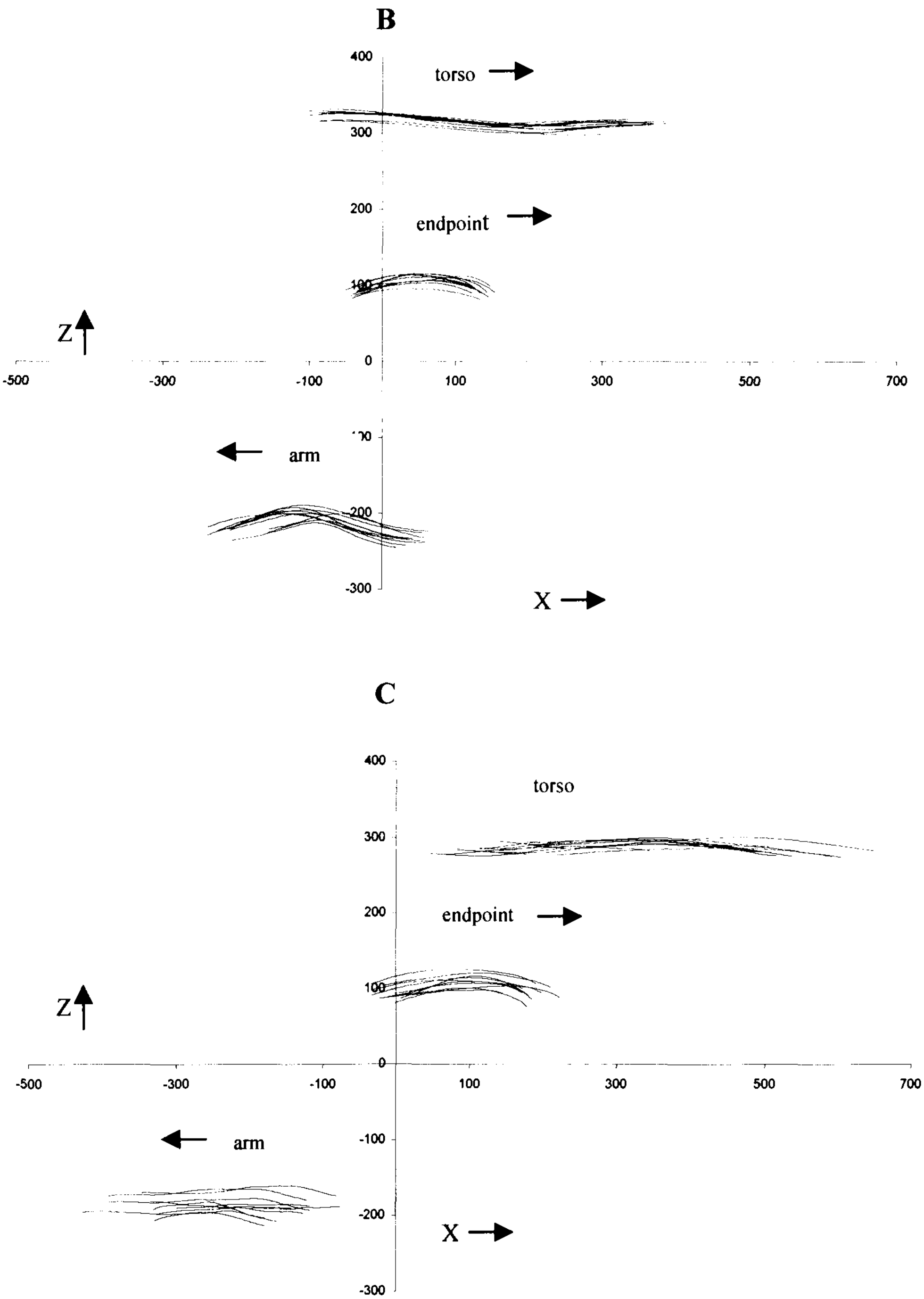


Figure 5.13: Spatial path plots (depicting horizontal (x) and vertical (z) displacement) for the torso, endpoint, and arm alone during cup transport for a single subject. A: Empty cup condition, B: Half full cup condition, C: Full cup condition. The arrows indicate the direction of the movement

It is interesting to note in all cases that while the movement of the torso and endpoint is largely in the positive x direction, the net movement of the arm alone is moving backwards. This reversal is the net result of the torso transporting the hand – via the locomotion system - from the start to the target position. Had the arm alone been transporting the hand to the target (as would have been the case if the subject was reaching while standing still), its net movement would have been in the positive direction. Rather, it would seem that the distance between the hand and the body stayed constant, and in all conditions, the cup was *walked* from point to point. Furthermore, just as in the approach plots, the transport figures show that in the empty cup condition (Figure 5.13A), the hand was ahead of the body at the time of grasp, and the body had to catch up; however, in the full cup condition (Figure 5.13C) the body was already ahead of the hand when the cup was lifted, and during transport, the hand lagged even further behind.

5.3.5 Spatial Variability

By observing the plots in Figures 5.12 and 5.13, one can begin to get some idea of the trial-to-trial spatial variability of the individual movement segments. We were interested in determining how this spatial variability changed across all subjects as a function of task condition both during approach and transport. Figure 5.14 represents the mean three-dimensional endpoint spatial path variability for each of the three levels of task complexity as the hand approached the cup. It is important to note that the spatial plots in Figures 5.12 and 5.13 depict movement in only two (i.e., x and z) dimensions. However, because the subjects in Experiment 3 were free to move in three-dimensional space, all measures reported here regarding variability have accounted for movement in each of the x, y, and z dimensions.

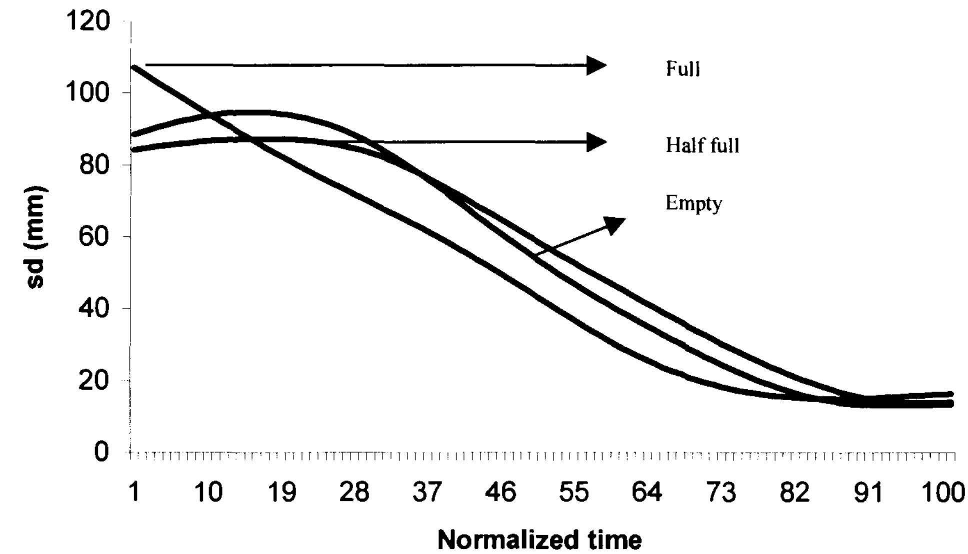


Figure 5.14: Mean normalized endpoint variance during approach as a function of task complexity.

Figure 5.14 shows that for each of the three experimental conditions of empty, half full and full cup, the spatial variability was decreasing for nearly the entire second preceding cup lift. When the cup was full, the decline had already begun at the start of collection. For the half full and empty cup conditions, there was a very slight increase for approximately the first 20% of the movement before the variability started to decrease. By the time cup lift had occurred (at the end of the 100 normalized frames), the variability had reached a minimum for all conditions. Repeated measures ANOVA for peak variability failed to reach significance ($F_{2,22}$=1.32, p=.21). However, it is important to recall that the approach phase of the prehensile action only captured the final 1000ms of movement prior to cup lift. Furthermore, the arms were in continuous motion while walking, and therefore the peak variability values that we compared are likely not true peaks. Therefore, while there was not a significant difference in peak variability during the final 1000 ms of the reach, a difference may have appeared had we been able to capture more data prior to cup lift. Interestingly however, the peak variability results do match those found in Experiment 2 for trunk-assisted reaching which also found no significant differences in peak variability. Also similar to the results of Experiment 2 was the finding that a significantly greater percentage of time was spent after peak variability for the full cup condition than either the half or the empty cup condition ($F_{2,22}$=10.3, p<.001).

Figure 5.15 depicts the spatial variability for each of the three complexity conditions during the transport phase of the movement. Looking at the Figure 5.15, it is apparent that there is little difference between the conditions in terms of their variability profiles. Note that the scaling for Figure 5.15 is consistent with that in Figure 5.14 which depicts the normalized variance during the approach phase. Subsequent statistical analysis confirmed that these differences, in terms of their peak values, were not significant ($F_{2, 22}$=1.17, p=.16). Furthermore, it is also apparent that the variability remains surprisingly consistent from when the cup is lifted until is replaced on the target position, to the point that the lines for the empty cup and the half full cup conditions are virtually superimposed.

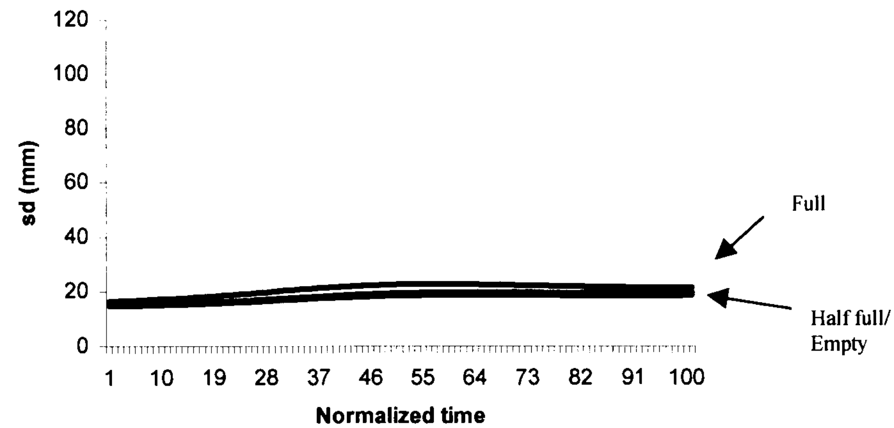


Figure 5.15: Mean normalized endpoint variance during transport as a function of task complexity.

We were also interested to see how the spatial variability of the segments (torso, endpoint, arm) changed during both the approach and transport phases of the movement. Figures 5.16A, B, C, D, E, and F depict the variability of the segments across each of the complexity conditions. The full expression of the movement segments, from the start of approach through the end of the transport, is presented in the side-by-side graphs of Figure 16. The graphs on the left (5.16 A, C, and E, or empty, half full, and full cup, respectively) depict the spatial variability of the torso, endpoint, and arm during the approach phase. One can see that in each case, the variability of the endpoint, though higher at the start of the movement, was the lowest of the three by the time the cup was lifted. Figures 5.16 B, D, and F show that this trend continued through until the task was completed. The individual data of four separate subjects are plotted in Appendix D to illustrate that the trends in Figure 5.16 are representative of the subjects within the group.

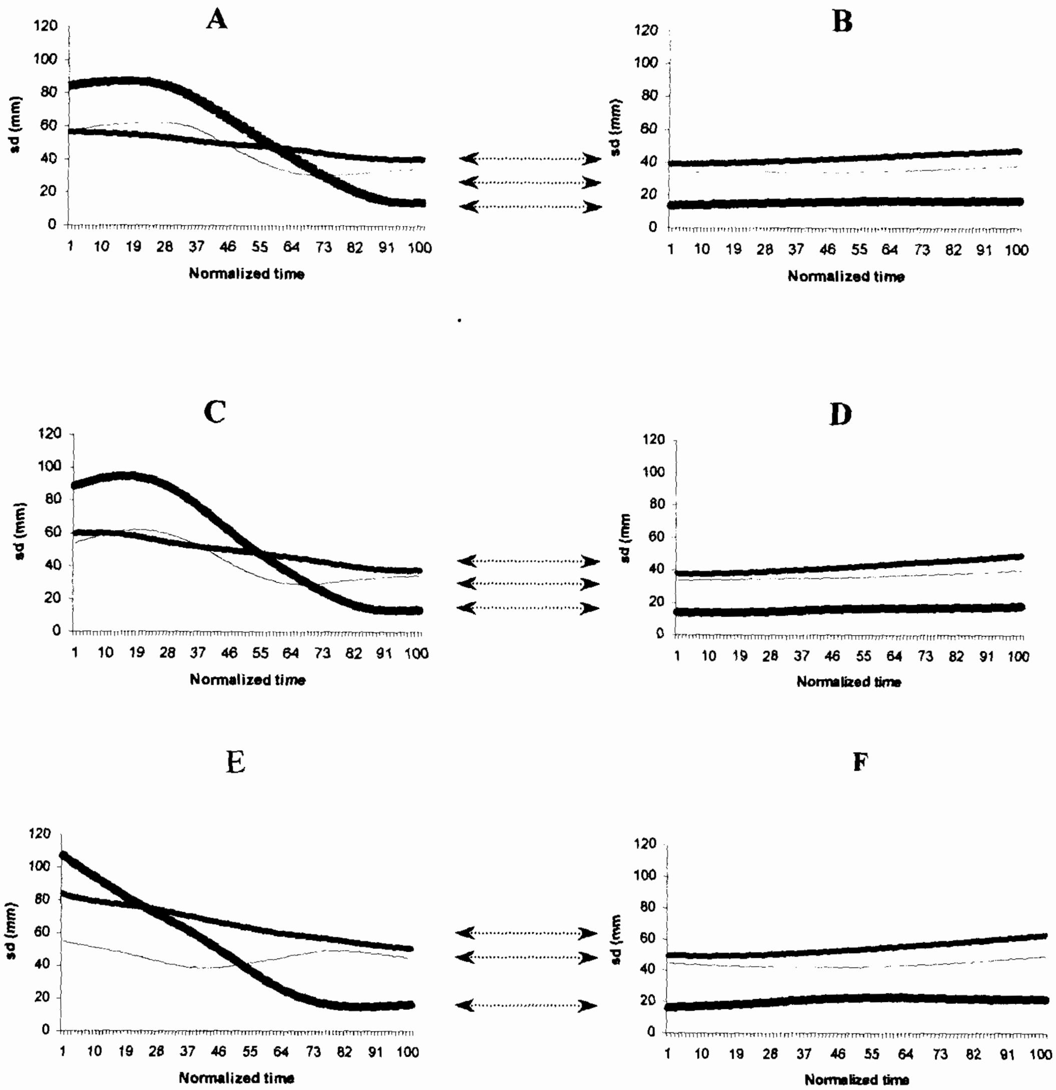


Figure 5.16. Segment variability plots during approach and transport. A: Empty cup condition during approach, B: Empty cup condition during transport, C: Half full condition during approach, D: Half full condition during transport, E: Full cup condition during approach, F: Full cup condition during transport. Heavy lines (▬▬) represent the endpoint; Medium lines represent the torso (——); thin lines (—) represent the arm alone.

5.4 Discussion

A primary goal of the current experiment was to acquire a greater understanding of how the motor control system adapts to meet the requirements of a task with increasing levels of complexity. In Experiment 3, task complexity was manipulated by having subjects reach for, grasp, and transport a cup that was empty, half full, or full of water while walking. Therefore, the full cup condition, by virtue of its increased "spillability", was defined as the most complex condition, followed by the half full and the empty cup conditions.

The kinematics of the upper limb were analyzed during both the approach (i.e., the reach to grasp) phase, as well as during the transport phase. Similar to the results of the Experiment 1, we found that movement velocity of the upper limb was affected by task complexity, in that higher peak values were achieved when subjects reached for empty versus full cups (Figure 5.1). In addition, more time was spent in deceleration when the cup was full than when it was empty. Taken together, these results indicate that velocity profile of the endpoint when walking is similar to traditional seated prehensile tasks. Because the reach is superimposed onto the regular arm swing during locomotion (Carnahan et al., 1997), the magnitudes of the wrist velocities are on a larger scale. However, even with the increased velocity and the additional movement segments, the hand nonetheless compensated for the precision requirements of the task by lengthening its deceleration phase (Marteniuk et al., 1987).

Not only did the hand move slower when task complexity was high, but the torso too was found to be moving slower when approaching full cup versus an empty or half full cup. This slowed torso movement in the full cup condition was largely the result of increases in stance times in the gait pattern at cup lift. It would seem that reaching to grasp a full cup of water while walking resulted in a general slowing pattern across the entire system. Once the gait pattern had slowed sufficiently by lengthening key stance phases, and the forward progress of the body was slowed, the reach was carried out almost as if the body was not moving at all. The spatial path plots of Figure 5.12 showed that even though the net movement of the arm actually reverses in direction, the endpoint still follows a relatively smooth trajectory. Furthermore, the peak variability of the endpoint did not statistically differ across complexity conditions, suggesting that although adding complexity resulted in changes to numerous features of the movement leading up to the grasp, the motor control system was able to maintain fairly consistent spatial trajectories. This finding is contrary to a report by Kudoh, Hattori, Numata, and Maruyama (1997) on spatial variability of the hand during seated reaching. These authors suggested that increases in spatial variability could be explained in terms of the speed-accuracy trade-off in Fitts' Law (Fitts, 1954). In other words, because larger movement amplitudes were shown to have larger movement times, and because these movements, with higher peak velocities, were found to also have higher peak values of variability, it was concluded that increased velocity meant increased variability (and therefore, decreased accuracy). We question this conclusion on the grounds that the three-dimensional variability of an entire movement trajectory does not necessarily correspond to the two-dimensional variability (error) about a target in an aiming task. First, there are an infinite variety of spatial paths that could be followed to reach the same point on a target. It is quite plausible then that a high degree of spatial variability could still result in low error. Furthermore, terminal accuracy is not the goal of a prehension task, nor was it specified to the subjects to move as quickly as they could. Their goal rather was to achieve a stable grasp on a cup, and transport it to a target without spilling its contents. Given these constraints, there is absolutely no reason to assume that just because a movement was performed faster, that it had to have been more variable, or even less accurate. In fact, because much of this task was presumably under the control of visual and proprioceptive feedback, especially when the cup was full, it is not surprising that slower movements could have increased variability due to on-line corrections. We will revisit this point later in the discussion.

During each trial, once the cup was grasped, the second part of the task was to transport the cup 15cm from the starting position to a target. The kinematic results for the transport phase were again similar to those reported in Experiment 1. More specifically, each of the landmark kinematic events reported were found to reflect the incremental increases in task complexity. Movement times for example (Figure 5.2), were shown to be fastest when transporting an empty cup, followed by the half full and the full cup conditions. Similarly, percent time from peak velocity was also found to increase as task complexity increased (Figure 5.3). These results are of particular interest because they suggest that a hand transporting an object behaves in a similar manner to a hand reaching to grasp an object. Although there are very few published papers on the subject, it has been suggested that these two tasks are under differential control (Mackey et al., 1999; 2000). At the very least, the results of the current experiment suggest that reaching to grasp an object and transporting one share certain kinematic features.

The results of the torso displacement data showed that increasing task complexity led to an increase in the role played by the torso in transporting the cup. These findings suggest that the motor control system protects against spilling the contents of the cup by keeping the hand in close proximity to the body during transport. The spatial path plots in Figure 5.12 show that the net movement of the arm is actually backwards, confirming graphically that the torso, not the arm, is responsible for carrying the hand from start to finish. As was the case with approach phase, what is perhaps most impressive about Figure 5.13 is how the endpoint trajectories remain smooth and consistent despite the changing nature of the components that produce these trajectories. These plots, along with those in Figure 5.16 that show the steadily decreasing and sustained variability of the endpoint, provide compelling support for a control mechanism that holds endpoint control in high priority.

The results of the within-subject spatial variability during the transport are again intriguing. Figure 5.17 juxtaposes the previously presented endpoint variability plots (Figures 5.14 and 5.15) for approach and transport across the three levels of task complexity.

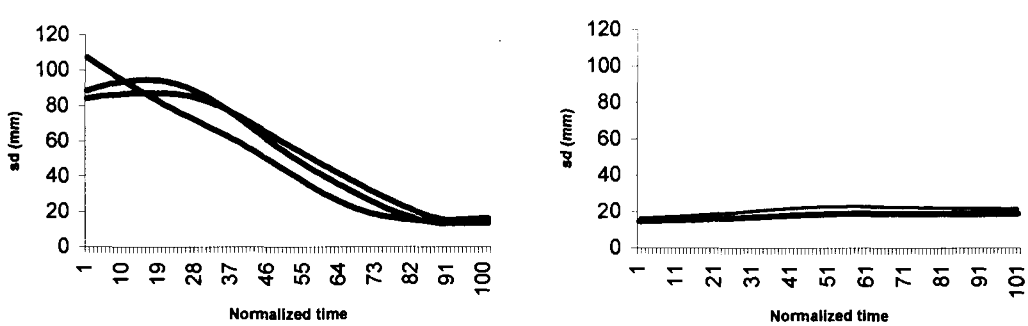


Figure 5.17: Endpoint variability during A) Approach, and B) Transport.

Viewed together, it is apparent that the level of variability that is achieved at the end of the approach phase (i.e., at cup lift) is maintained throughout the transport of the cup. This consistency across complexity conditions occurs despite significant differences in movement time, peak velocity, and deceleration time. In this instance, it would appear as though neither velocity, nor the velocity profile had much to do with the variability of the spatial trajectories. As was the case with the variability during the approach phase, these somewhat counterintuitive results can be reconciled if one considers the nature of the task. In order to transport a cup full of water from one place to another, the subjects in this experiment needed to rely a great deal on visual feedback throughout the task. Therefore, the increased variability that may have resulted due to faster movement times could have been counterbalanced by an increase in the number of on-line corrections during the slower, more complex task conditions. To put it another way, it may be that under certain circumstances, including perhaps ballistic aiming tasks, the velocity of a movement may be correlated with its variability; however, to imply that speed alone causes variability is understating the issue.

A final point of discussion relates to the notion of motor equivalence, or how invariant ends can be achieved through variable means. There are two parts to this definition, and each should be considered separately. First, within the context of Experiment 3, the 'variable means' could be seen in how each of the involved systems (gait, torso, prehension) was found to alter it pattern of action in response to increases in task complexity. For example, the gait pattern was adjusted to provide a better opportunity to achieve a successful grasp. Likewise, subjects rotated more at the torso toward the cup when it was full versus when it was half full or empty. Finally, the prehension system was found make similar adjustments as task complexity increased, and was simultaneously required to compensate for the changing contributions of the gait and torso systems in order to keep the hand in a position to complete the grasp. Each of these adjustments at the level of the individual systems go together to create a highly variable means of performing an action.

Regarding the 'invariant end', there are two ways to understand this idea within the context of the current experiment. First and foremost is that the goal of the task (i.e., a successful grasp and transport) was consistently achieved. The end, therefore, can be seen as successful task completion. Interestingly however, we also noticed that the magnitude of the endpoint variability was not significantly different across the conditions of task complexity. It could be suggested therefore that one way the motor control system is able to consistently achieve a successful grasp while walking is through a high level strategy to maintain a consistent spatial trajectory. In order to do so, it is clear that all of the underlying systems and their associated degrees of freedom must be orchestrated into a single, functional synergy whose purpose it is to keep the hand on plane when approaching the to-be-grasped object. In other words, the individual systems must essentially become one goal-oriented motor system.

Chapter 6: General Discussion

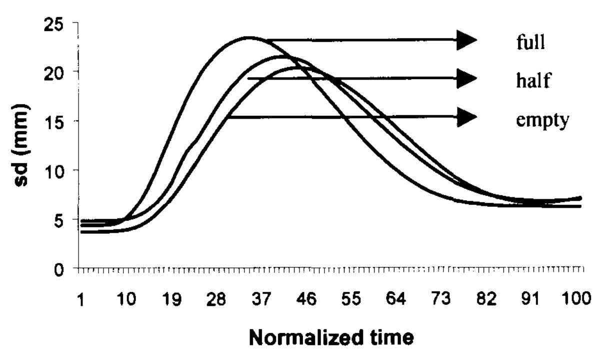
Although each of the three experiments presented herein possessed its own unique series of purposes, the common theme that emerged throughout this work was the way in which multiple muscle systems can be organized into a single, functional unit, and how that organization can be understood within the framework of motor equivalence. Each of the experiments contained herein brought to light novel results, and built upon the experiment that preceded them.

Beginning with Experiment 1, we showed that when complexity was added to a prehension task involving locomotion, the pattern of locomotion was altered to provide a better opportunity for a successful grasp to be achieved. Furthermore, the kinematic pattern of the upper limb was also modified in order to account for the complexity requirements of the task. Combined, these results provided a nice initial demonstration of how the two independent systems of prehension and gait can be coordinated to bring about successful task goals.

Recognizing that a combined locomotion/prehension task, by its nature, requires the involvement of the torso, Experiment 2 was designed to first investigate in depth how the arm and torso work together during prehension, and second to arrive at a strategy for including the torso in a later task (i.e., Experiment 3) which would again incorporate locomotion. The results of Experiment 2 proved to be very informative. First, we showed that adding complexity to a trunk-assisted prehension task by increasing the water level of a to-be-grasped cup impacted the kinematic profiles of both the transport and grasp components of the movement. It was also discovered that the involvement of the torso changed depending on the level of water in the cup. This was found to be the case not only for the amount of actual displacement of the torso, but also for its velocity profile. More specifically, increasing task complexity resulted in the torso displaying a precision effect, or an increase in the percentage of time spent in deceleration. Interestingly however, despite the changes in both systems in response to the changing task demands, consistent endpoint trajectories were nonetheless maintained across task conditions. We found no statistical differences in the amount of endpoint variance as a result of increasing task complexity, and further, we showed that the variability of the endpoint decreased to a greater extent throughout each condition than did either the torso or the arm alone. We feel that this ability of the motor system to coordinate two independent systems into one, functional neuromuscular synergy – one that allows for consistent endpoint trajectories – reveals an excellent illustration of motor equivalence.

Experiment 3 sought to combine what was learned in the first experiment regarding simultaneous locomotion and prehension with that which was learned in the second experiment concerning the coordination of the arm and torso. An additional challenge of Experiment 3 was that it involved not only reaching to grasp an object while walking, but also that it required the object to be transported from one position to another. Regarding the reach to grasp, or approach phase of the movement, we found striking similarities between the kinematic features of the kinematic features of the upper limb in Experiment 2 (i.e., trunk-assisted prehension and those of Experiment 3 in which prehension was assisted by locomotion. In both cases, the results for peak velocity and deceleration time showed the same effect of task complexity despite the fact that in Experiment 3, the reaching arm was being transported by the gait system, and was therefore moving at a much higher rate of velocity. Moreover, the patterns of variability were similar during both seated reaching and while walking. Figures 6 A, B, C, and depict the previously presented graphs of variability from Experiments 2 (A and C) and 3 (B and D). Note however, that because there was no distinct starting point for the reach during walking (Figures 6B and D), and that the data represent only the final second prior to cup lift, the profiles are somewhat abbreviated at their start. Nonetheless, it is apparent that the patterns of variability for Experiment 3 bear striking resemblance to those of Experiment 2.

A



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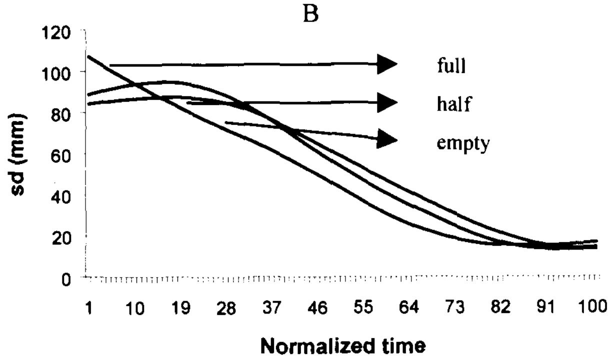
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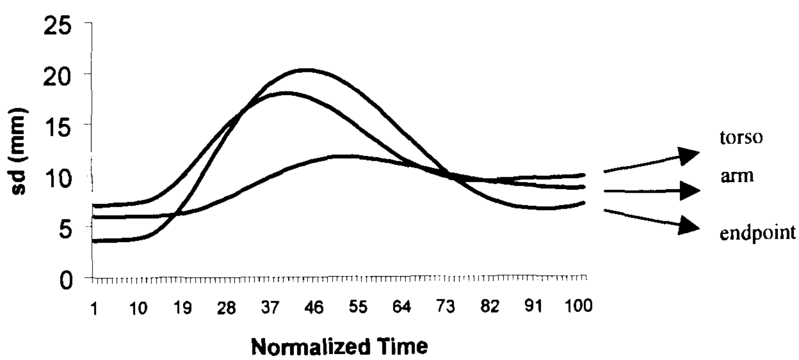
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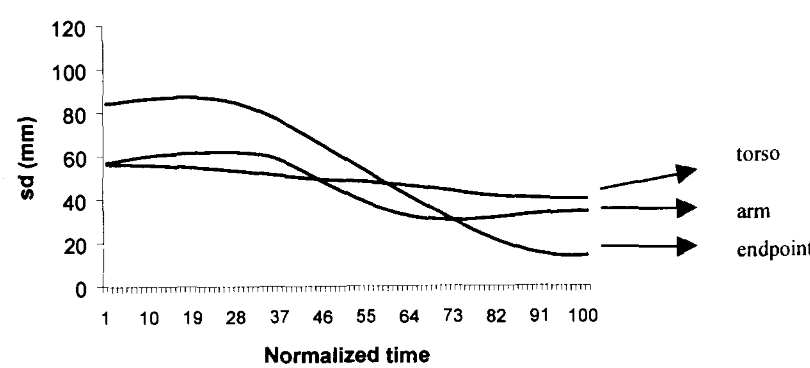
D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endpoint
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Figure 6.1: Variability plots. A) Endpoint variability (Experiment 2); B) Endpoint variability (Experiment 3:approach); C) Segment variability when grasping an empty cup (Experiment 2); D) Segment variability when grasping an empty cup (Experiment 3:approach).

Whether the reach was performed while walking or while seated, these systematic patterns of within-subject variability suggest that a high-level priority of this sensorimotor-based control system is to consistently place the end effector in an optimal position for grasping the object (Marteniuk & MacKenzie, 1990). In other words, the recurring variability patterns of the endpoint, arm, and chest (Figure 6.1 C and D) – particularly with the endpoint variability decreasing to the greatest extent – imply that endpoint control is a significant factor in the planning and execution of prehension tasks of all kinds.

Taken together, the kinematic and variability results of Experiments 2 and 3 suggest not only that the reach is superimposed onto the arm swing during locomotion, but also that reaching to grasp while seated and reaching to grasp while walking are remarkably analogous despite being carried out by different systems. Given the number of degrees of freedom that needed to be controlled in Experiment 3, it is a truly impressive feat of coordination that the motor control system was able to carry out this task in such a seemingly effortless way, and further, in a manner that so strongly resembles a regular, seated reaching movement. These findings again speak to the idea that multijoint coordination is accomplished, at least in part, by constructing a single, functional movement synergy from several independent and subservient movement systems.

An important question that remains regarding the experiments presented in this dissertation relates to the control mechanisms that would allow for coordination over such a large number of degrees of freedom. In Experiment 2, the seated prehension movement first required the arm and torso to work together to transport the hand to the object, followed by the hand having to compensate for added torso movement and to achieve a successful grasp. With the addition of locomotion to Experiments 1 and 3, the motor control system had the additional burden of accounting for the fact that the arm was being transported to the object via the gait system, and therefore needed to make compensations not only for the additional forward velocity, but also for the regular up and down motion of the body that accompanies locomotion.

It would seem at the outset that the variability of the individual movement systems observed in these experiments - both in terms of the spatial path plots and the varying contributions of the different body segments - would speak against the notion of a single motor program or synergy. For example, the strategies adopted in Experiment 3 to grasp full cups of water were vastly different than were the strategies for grasping empty cups. In light of these data, it is instead suggested that the compound movements discussed herein are controlled by a more flexible series of motor commands. One such versatile control mechanism is Arbib's (1981) notion of the coordinated control program. Arbib's distributed model was useful for explaining the coupling of the transport and grasp components of prehension. Central to Arbib's claim was the idea that a motor program need not imply specified or fixed-sequence behaviour. He suggested instead that movements are allowed to evolve according to peripheral as well as central inputs. Arbib also spoke of high-level goals and lower level motor outputs as a possible means for controlling degrees of freedom.

Abbs et al. (1984) further suggested that a motor program is a representation of the dynamic processes of movement, whereby appropriate sensorimotor contingencies are set up to ensure cooperative contributions of multiple actions to achieve a common predetermined goal. Such a construct was set up by the authors to explain the corrections observed in speech perturbation research. Essentially, Abbs et al. (1984) showed that when a perturbation was applied to one sub-component of a speech movement (i.e., the lower lip), adjustments were seen in the lower lip (termed autogenic), as well as in the upper lip and jaw (termed feedforward). The defining feature of these and other related studies was that despite the perturbations, successful sound production was consistently achieved. Again, it would appear as if the task of the motor system was to achieve the goal successfully, using all means available. Abbs et al. (1984) also drew parallels between speech production and upper limb activities:

> "Specifically, involving a multimovement gesture involving subcomponents (sic) A, B. and C (elbow, wrist, and finger, or upper lip, lower lip, and jaw), one might hypothesize that the final contribution of each of these subactions is determined by sensorimotor, feedforward controllers operating independently on afferent information from A, B, and C, and guided by an abstract, goal-directed plan of action" (p. 213).

The sub-components of the compound movements described in this dissertation could be characterized in a similar way. In other words, sub-components A, B, and C would correspond to hand, torso, and gait, with each independently contributing as necessary to ensure the successful completion of the movement goal. We have attempted to capture the essence of this model of organization in Figure 6.2.

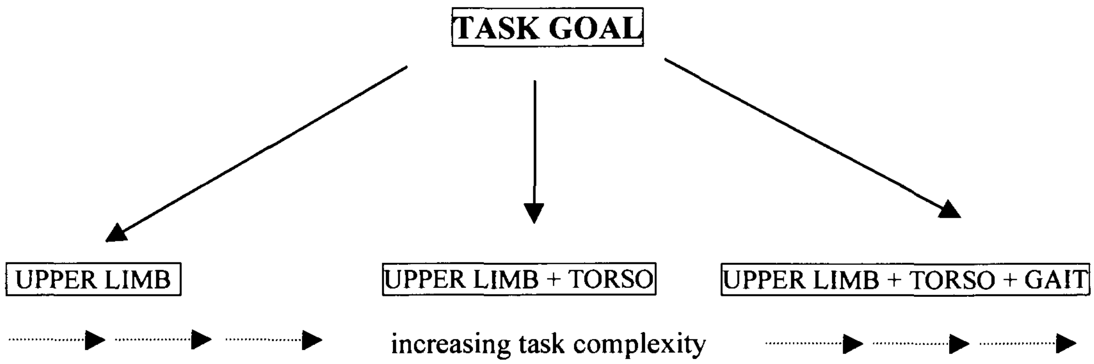

Figure 6.2: Hierarchical-distributed model for compound movements involving prehension.

Figure 6.2 is presented as a possible hierarchical-distributed representation of a compound movement involving the upper limb, torso, and gait. At the top of the hierarchy sits the overall representation of the movement goal. Below the task goal are the individual segments involved that could possibly be recruited in order to successfully carry out a prehension task that involved movement of the torso and/or locomotion. According to this model, the *method* of achieving the goal (i.e., upper limb alone, upper limb + torso, etc.) is subordinate to, and dependent upon the demands of the task. It is postulated that in the case of a very simple prehension task, the upper limb alone would be capable of making the necessary adjustments to successfully complete the task. For movements of moderate complexity, adjustments would be made in parallel in the upper limb and torso. Finally, for complex movements that require locomotion to bring the to-be-grasped object in to range, parallel adjustments would be seen in the hand, torso and gait. Several studies support such a model. For example, the Carnahan et al. (1996) study employed the fairly simple manipulation of dowel size. Their findings fit the current model in that the majority of the adjustments made to accommodate changes in dowel size were seen at the level of the hand. It should be noted however, that these authors did not measure kinematic features of the torso. Indeed, it would be interesting to discover if there were torso contributions to the overall movement. The work of Marteniuk et al. (2000) was likewise consistent with the present model. In a pointing task involving locomotion, these authors noted that decreasing the size of the target affected both the kinematics of the hand, and the contribution of the torso. In other words, when subjects required more precision, the torso contributed more toward helping the hand maintain the speed and accuracy of the task. A prediction based on the current model would suggest that as an upper limb task continued to increase in complexity, adjustments would be seen in gait characteristics. This prediction was realized in Experiments 1 and 3 of the current work. In Experiment 3 for example, increasingly longer stance phases were reported at the time of cup lift as task complexity increased.

The above model can also account for the inconsistencies mentioned earlier in the trunk-assisted reaching literature. To review, Saling et al. (1996) suggested that trunk kinematics were unaffected by changes in dowel size. If one considers that the two dowels were of equal height and similar diameter (2.2 cm and 6.7 cm), it is reasonable to assume that the task was simple enough, and the conditions similar enough to have all adjustments made at the level of the hand. In keeping with the current model, the results of Experiment 2 showed that the torso played a substantially different role in the movement when the cup was full versus when it was empty. When reaching for the full cup, the torso moved a greater distance and decelerated for a longer period of time than when the cup was empty. Similar results regarding the role of the torso in trunk-assisted prehension have been reported elsewhere in the literature, both for neurologically intact individuals (e.g., Mackey et al., 2000; Steenbergen et al., 1995), as well as in neurologically impaired subjects (e.g., Van Thiel & Steenbergen, 2001; Cristea & Levin, 2000).

The combined results of the present experiments also indicated that the endpoint (i.e., the hand) trajectories remained consistent despite the large number of contributing degrees of freedom. This finding was illustrated nicely in Experiments 2 and 3 by contrasting the spatial trajectories of the endpoint to those of the arm relative to the body. In Experiment 3 for example, the displacement of the endpoint followed a normal bell-shaped spatial trajectory despite the fact that the net movement of the arm was in the reverse direction. In other words, the motor control system seems highly efficient in sending compensatory commands to the hand to counteract the movement of the body. Furthermore, the motor control system seems equally adept at transforming at least four independently operating synergies (i.e., the reach, the grasp, the torso, and the gait) into a single, optimal synergy to satisfy the demands of the task. In terms of the task goal itself, it is important to note that successful grasps were consistently achieved despite highly variable reach-to-grasp strategies. This invariant end, or the accomplishing of task goals despite highly variable means is the hallmark of the principle of motor equivalence. The results contained in this dissertation provide a strong demonstration of motor equivalence and we believe that this work begins a systematic exploration of the underlying parameters of this phenomenon. More specifically, our work shows one variable that appears related to the emergence of motor equivalence is the variable of task complexity.

A final note is in regard to our choice in studying unrestrained movements as the focal point for this work. It was mentioned at the outset of this dissertation that the study of relatively natural movements has both its benefits and its pitfalls. Indeed, providing a rigorous analysis of movements that involve so many of the body's motor systems is by no means a trivial task. If we have succeeded in this regard to some extent, than this dissertation should be deemed a success. And finally, although these experimental designs create new challenges for data collection and analyses, we hope that these new challenges do not deter, but rather encourage researchers to new experimental ground upon which to observe the full and articulate expression of the human motor system.

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Appendix A:

Table 1: Mean values and standard errors (in parentheses) of dependent measures describing upper limb characteristics when reaching for covered and uncovered cups with the intent of transporting the cup to one of three amplitudes (15cm, 30cm, and 45cm).

Approach Phase	Covered	Uncovered	15cm	30cm	45cm	Significance
Peak Velocity (mm/s)	1823 (39)	1610 (106)	1710 (94)	1712 (99)	1728 (95)	**A**
Time after PV (ms)	801 (21)	902 (7)	872 (15)	854 (18)	829 (10)	C

A: Significant Cup main effect ($p<0.05$)
B: Significant Amplitude main effect ($p<0.05$)
C: Significant Cup x Amplitude interaction ($p<0.05$)

Table 2: Mean values and standard errors (in parentheses) of dependent measures describing upper limb characteristics when transporting covered and uncovered cups to one of three amplitudes (15cm, 30cm, and 45cm).

Transport Phase	Covered	Uncovered	15cm	30cm	45cm	Significance
Movement time (ms)	545 (22)	715 (28)	453 (15)	647 (27)	790 (30)	**A, B**
Peak Velocity (mm/s)	748 (26)	613 (27)	471 (15)	680 (21)	891 (41)	**A, B**
Time to PV (ms)	218 (11)	290 (14)	182 (13)	256 (14)	325 (18)	C
% Time to PV	39.4 (1)	40.7 (1.2)	39.4 (1.4)	39.4 (1.1)	41.4 (1.0)	C
Time after PV (ms)	329 (15)	428 (18)	275 (13)	397 (18)	465 (20)	C
% Time after PV	60.1 (0.9)	59.5 (1.1)	60.6 (1.4)	60.8 (1.0)	58.5 (1.0)	C

A: Significant Cup main effect ($p<0.05$)
B: Significant Amplitude main effect ($p<0.05$)
C: Significant Cup x Amplitude interaction ($p<0.05$)

Table 3: Mean values and standard errors (in parentheses) of dependent measures describing gait characteristics of stance phases prior to and during cup lift and replace for a covered cup.

LIFT					
Pre-lift stance	Lift stance	Significance	Pre-lift swing	Lift swing	Significance
725 (15)	814 (18)	*	438 (8)	482 (13)	n/s
REPLACE					
Pre-replace stance	Replace stance	Significance	Pre-replace swing	Replace swing	Significance
737 (14)	820 (18)	*	442 (8)	475 (14)	n/s

*: Significant at $\alpha < 0.005$

Appendix A: (cont'd)

Table 4: Mean values and standard errors (in parentheses) of dependent measures describing gait characteristics when grasping and transporting covered versus uncovered cups 15cm.

Phase of Locomotion	Covered	Uncovered	Significance
Stance time at cuplift (ms)	814 (18)	899 (29)	*
Swing time at cuplift (ms)	482 (13)	490 (7)	n/s
Stance time at cup replace (ms)	820 (18)	917 (27)	*
Swing time at cup replace (ms)	475 (14)	502 (14)	*

*: Significant at $\alpha < 0.005$

Appendix B:

Table 1: Mean values and standard deviations (in parentheses) of dependent measures describing upper limb characteristics when reaching to grasp cups that were either empty, half full, or full of water.

The upper limb (endpoint)	Empty	Half	Full	Significance
Movement time (ms)	826 (189)	909 (191)	1153 (172)	A
Peak Velocity (mm/s)	840 (163)	813 (157)	763 (135)	A
Time after PV (ms)	379 (80.5)	380 (77)	401 (80)	A
% Time after PV	40.2 (10)	46.8 (8.0)	57.9 (8.2)	A
Peak aperture (mm)	105 (8.6)	103 (7.8)	104.7(6.2)	n/s
% Time after peak aperture	22.7 (4.4)	28.2 (3.5)	40.4 (6.5)	A
Peak spatial variability (mm)	17.3 (5.1)	19.0 (5.7)	19.0 (6.6)	n/s
% Time to peak spatial variability	47 (8.5)	43.1 (8.1)	39 (6.8)	A

A: Significant Cup main effect ($p<0.05$)

Table 2: Mean values and standard deviations (in parentheses) of dependent measures describing characteristics of the torso movement when reaching to grasp cups that were either empty, half full, or full of water.

The torso	Empty	Half	Full	Significance
Displacement (mm)	128.6 (38.7)	137.2 (37.5)	149.7 (37.9)	A
Movement time (ms)	839 (188)	907 (235)	1190 (206)	A
Peak Velocity (mm/s)	296 (68)	310 (76)	306 (66)	n/s
Time after PV (ms)	383 (108)	444 (145)	719 (144)	A
% Time after PV	45.3 (6.6)	48.5 (5.5)	60.4 (4.7)	A

A: Significant Cup main effect ($p<0.05$)

Table 1: Mean values and standard deviations (in parentheses) of dependent measures when reaching for cups that were either empty, half full, or full of water.

Approach Phase	Empty	Half	Full	Significance
Peak Velocity (mm/s)	2044 (284)	2051 (393)	1491 (338)	A
Time after PV (ms)	775 (131)	815 (136)	948 (52)	A
Peak spatial variability (mm)	86.1 (25.6)	95.3 (26.3)	108.9 (29.8)	n/s
% Time after peak spatial variability	85 (11.2)	87 (10.4)	98 (6.2)	A
Torso Displacement (mm)	1124 (167)	1093 (188)	727 (182)	A
Torso Rotation (degrees)	3.9 (2.3)	4.1 (2.6)	8.2 (4.8)	A
Torso Flexion (degrees)	2.5 (1.6)	2.6 (1.9)	4.4 (3.6)	A

A: Significant Cup main effect ($p<0.05$)

Table 2: Mean values and standard deviations (in parentheses) of dependent measures describing the transporting cups that were either empty, half full, or full of water.

Transport Phase	Empty	Half	Full	Significance
Movement time (ms)	343 (56)	419 (59)	610 (95)	A
Peak Velocity (mm/s)	554 (37)	488 (26)	403 (35)	A
Time after PV (ms)	198 (54)	234 (52)	381 (90)	A
% Time after PV	55.1 (7.1)	57.0 (7.1)	61.5 (7.7)	A
Peak spatial variability (mm)	22.1 (7.2)	20.3 (6.7)	19.4 (6.3)	n/s
Torso Displacement (mm)	314 (32)	357 (48)	353 (61)	A
Torso Rotation (degrees)	4.3 (3.3)	5.3 (3.2)	4.8 (2.3)	n/s
Torso Flexion (degrees)	2.8 (1.3)	2.0 (1.1)	2.6 (1.7)	n/s

A: Significant Cup main effect ($p<0.05$)

Table 3: Mean values and standard errors (parentheses) of dependent measures comparing stances phases prior to cup lift and replace with stance phases at the actual time of cup lift and replace.

	Pre-lift stance	Lift stance	Sig.	Pre-replace stance	Replace stance	Sig.
Empty	665 (15)	716 (17)	n/s	663 (16)	721 (15)	n/s
Half	659 (16)	795 (41)	n/s	669 (18)	816 (33)	n/s
Full	688 (15)	870 (42)	*	712 (18)	889 (46)	*

*: Significant at $\alpha < .005$

Table 4: Mean values and standard errors (parentheses) of dependent measures describing gait characteristics when transporting cups that were either empty, half full or full of water.

Phase of Locomotion	Empty	Half	Full	Significance
Stance time at cuplift (ms)	716 (17)	795 (41)	870 (42)	**A**
Swing time at cuplift (ms)	425 (5)	422 (8)	435 (8)	n/s
Stance time at cup replace (ms)	721 (15)	816 (33)	889 (46)	**A**
Swing time at cup replace (ms)	441 (11)	480 (15)	486 (18)	n/s

A: Significant Cup main effect ($p<0.05$)

Appendix D:

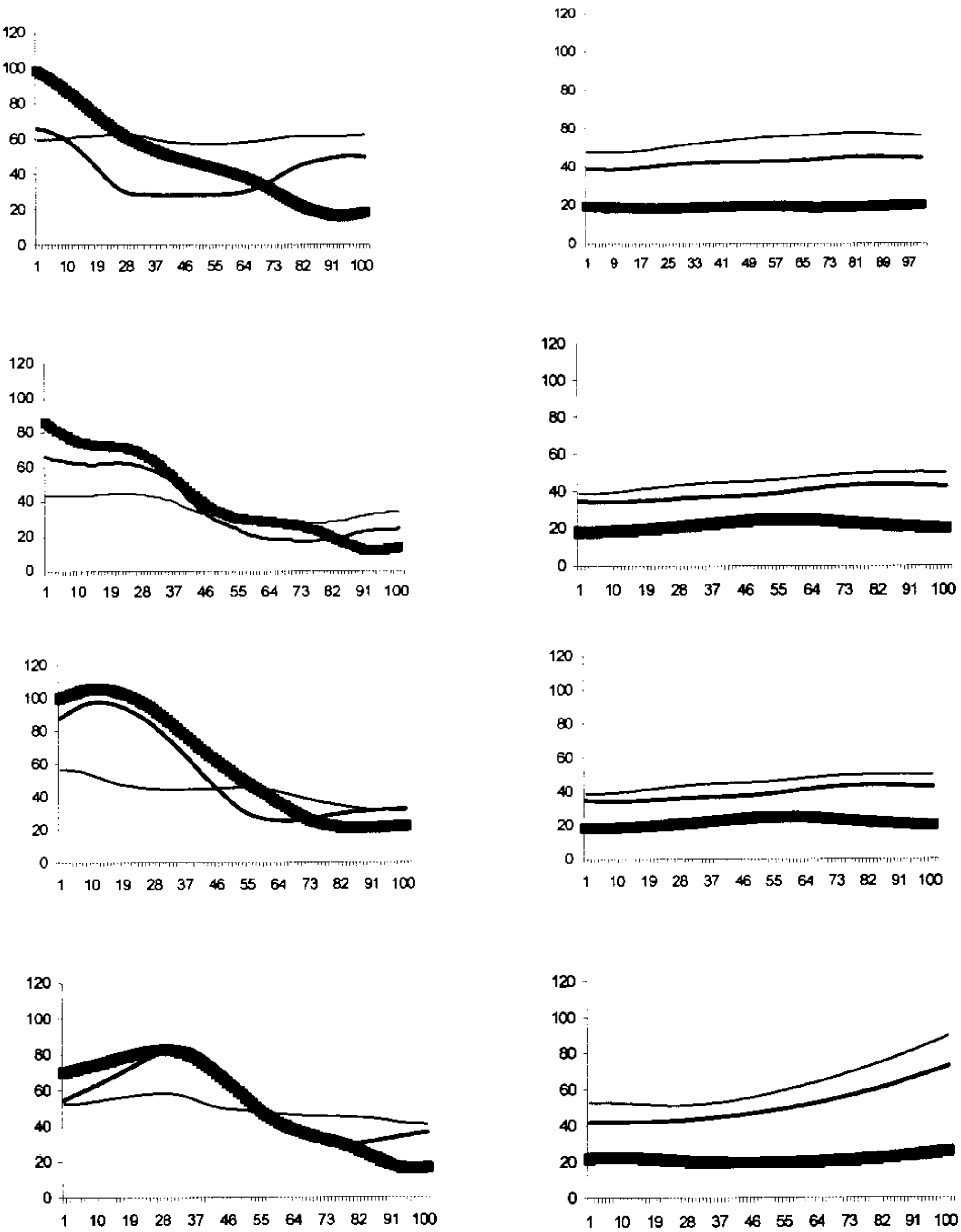
Approach Transport

Sub01

Sub03

Sub06

Sub07



Appendix A. Segment variability plots for 4 separate subjects during approach and transport. Heavy lines (▬) represent the endpoint; Medium lines represent the torso (——); thin lines (—) represent the arm alone.

Appendix E:

1. Endpoint Movement Time

Descriptive Statistics

	Mean	Std. Deviation	N
MTE	825.8000	189.78764	15
MTH	909.1259	191.25716	15
MTF	1153.2000	171.85322	15

		MTE	MTH	MTF
MTE	Pearson Correlation			
	Sig. (2-tailed)	.	.000	.251
	N	15	15	15
MTH	Pearson Correlation	.822**	1	.585*
	Sig. (2-tailed)	.000	.	.022
	N	15	15	15
MTF	Pearson Correlation	.316	.585*	1
	Sig. (2-tailed)	.251	.022	.
	N	15	15	15

**

*.

2. Endpoint Peak Velocity

Descriptive Statistics

	Mean	Std. Deviation	N
PVE	840.2487	163.42602	15
PVH	812.8058	156.93734	15
PVF	763.7220	135.28781	15

Correlations

		PVE	PVH	PVF
PVE	Pearson Correlation	1	.743**	.634*
	Sig. (2-tailed)	.	.001	.011
	N	15	15	15
PVH	Pearson Correlation	.743**	1	.861**
	Sig. (2-tailed)	.001	.	.000
	N	15	15	15
PVF	Pearson Correlation	.634*	.861**	1
	Sig. (2-tailed)	.011	.000	.
	N	15	15	15

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Appendix E: (cont'd)

3. Torso Movement Time

Descriptive Statistics

	Mean	Std. Deviation	N
VAR00002	838.8000	187.68132	15
VAR00003	907.4519	235.22918	15
VAR00004	1189.9000	206.81861	15

Correlations

		VAR00002	VAR00003	VAR00004
VAR00002	Pearson Correlation	1	.788**	.393
	Sig. (2-tailed)	.	.000	.147
	N	15	15	15
VAR00003	Pearson Correlation	.788**	1	.363
	Sig. (2-tailed)	.000	.	.184
	N	15	15	15
VAR00004	Pearson Correlation	.393	.363	1
	Sig. (2-tailed)	.147	.184	.
	N	15	15	15

**. Correlation is significant at the 0.01 level (2-tailed).

4. Torso Peak Velocity

Descriptive Statistics

	Mean	Std. Deviation	N
VAR00005	296.0203	67.72716	15
VAR00006	309.9193	76.44796	15
VAR00007	306.1481	66.05128	15

		VAR00005	VAR00006	VAR00007
VAR00005	Pearson Correlation	1	.96 **	.90 **
	Sig. (2-tailed)	.	.000	.000
	N	15	15	15
VAR00006	Pearson Correlation	.96 **	1	.93 **
	Sig. (2-tailed)	.000	.	.000
	N	15	15	15
VAR00007	Pearson Correlation	.90 **	.93 **	1
	Sig. (2-tailed)	.000	.000	.
	N	15	15	15

**

Appendix E: (cont'd)

5. Torso Displacement

Descriptive Statistics

	Mean	Std. Deviation	N
EMPTY	128.6374	38.77131	15
HALF	137.2483	37.50324	15
FULL	149.7719	37.92475	15

Correlations

		EMPTY	HALF	FULL
EMPTY	Pearson Correlation	1	.908**	.929**
	Sig. (2-tailed)	.	.000	.000
	N	15	15	15
HALF	Pearson Correlation	.908**	1	.936**
	Sig. (2-tailed)	.000	.	.000
	N	15	15	15
FULL	Pearson Correlation	.929**	.936**	1
	Sig. (2-tailed)	.000	.000	.
	N	15	15	15

**. Correlation is significant at the 0.01 level (2-tailed).

6. Peak Aperture

Descriptive Statistics

	Mean	Std. Deviation	N
PAE	105.0826	8.63730	15
PAH	102.6507	7.77748	15
PAF	104.7822	6.21965	15

Correlations

		PAE	PAH	PAF
PAE	Pearson Correlation	1	.861**	.792**
	Sig. (2-tailed)	.	.000	.000
	N	15	15	15
PAH	Pearson Correlation	.861**	1	.747**
	Sig. (2-tailed)	.000	.	.001
	N	15	15	15
PAF	Pearson Correlation	.792**	.747**	1
	Sig. (2-tailed)	.000	.001	.
	N	15	15	15

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix F:

FORM 1

SIMON FRASER UNIVERSITY

REQUEST FOR ETHICAL APPROVAL OF RESEARCH

This form must be completed and submitted along with the Checklist and other required documents to the Office of the Vice-President, Research, by any faculty, staff or student involved in, for example, the following: independent study program, honours or graduate thesis work, who is proposing to carry out a project involving human subjects whether or not financial support for the proposed research is being sought.

NOTE: Responsibility for determining the ethical acceptability of the design and conduct of **other** student research which is carried out in fulfillment of course requirements and which involves human subjects rests with the department or Faculty in which the course is taught.

PRINCIPAL INVESTIGATOR'S NAME (please type or print clearly)
Chris Bertram

Position: __ **Undergraduate** _X_ **Graduate Student** ________ **Other (specify)**

___ **Post Doctoral** ___ **Faculty (type of appt.)**________________

Dept./School/Faculty: School of Kinesiology, Faculty of Applied Sciences

Phone: 291 – 5794 **(w)**__________**(h)**

Fax: ______________ **Email address:** chrisb@move.kines.sfu.ca

CO-INVESTIGATOR'S NAME (if applicable):
Dr. Ron Marteniuk

FACULTY SUPERVISOR'S NAME (if applicable):

Dr. Ron Marteniuk **email address:** rmarteni@move.kines.sfu.ca

TITLE OF PROPOSED RESEARCH: Co-ordination during a Combined Locomotion/Prehension Task.
Funded by: NSERC

Is the title of this Ethics study identical to the one submitted to the funding agency? _X_ Yes; ____No.
If "No" what is that title?

____

Proposed starting and expected end date of the research project:

Start date: July 21, 1999 ____ **Expected end date:** September 30, 1999

Note: If you are applying for a multi-year grant you must submit a Request for Ethical Approval of Research for **each project** involving human subjects to be funded by that grant. Ethical approval for one project involving human subjects funded by a grant does not apply to other projects funded by that grant.

PLEASE CHECK THE APPROPRIATE ANSWER:	YES	NO
1. **Will children be involved as subjects in your research?** If YES, a consent form for the parent/guardian must be used. (See sample Form #3 as an example upon which your form should be modeled). **NOTE:** On a separate piece of paper, you should also explain how you will seek informed, voluntary consent from children old enough to provide it themselves.	___	X
2. **Will any part of the research project be undertaken by students?** If YES, note that students are not protected under Section 68 of the Universities Act, nor do they enjoy full protection under Simon Fraser University's liability insurance policies.	X	___

3. **Explain who your subjects or participants are and how you locate them.**
We will use SFU students as subjects and will locate them by a variety of methods. We will send out an e-mail to the SFU kinesiology undergraduate mailing list requesting paid participation for a motor control experiment. As well we will post a sign-up sheet on the lab door and rely on word of mouth to recruit subjects.

	YES	NO
4. **Will your subjects be chosen from a captive population (i.e. school children or prisoners)?** If YES, a Parent/Guardian Consent Form must be used. (See Sample Form #3). If the subject is capable of giving informed consent, a Subject Consent Form is also required. (See Sample Form #2).	___	X
5. **Will you be asking your subjects to participate in a project involving completion of an interview, questionnaire, survey, or similar instrument?**	___	X

If YES:

___ (a) Attach a copy of the instrument to be used.

___ (b) Attach a paragraph or more in which you state what steps you will take to secure informed consent of your subjects to their participation; to secure parent or guardian consent where appropriate; to allow subjects the option of withdrawing participation, partially or fully, at any time; and to ensure the continued security or safe disposal of the materials accumulated in the study after the research is completed.

	YES	NO
6. **Will you be asking your subjects to participate in a project other than one involving completion of an interview, questionnaire, survey, or similar instrument?** If YES, a Subject Consent form must be used (See Sample #2).	X	___

7. Explain briefly the nature of subject participation.
NOTE: Appending a lengthy thesis proposal or other document does not substitute for completion of this section.

Subjects will be asked to walk, at their own pace, past a table, pick up a cup filled with water and move it to a location ahead of the pick up position. Subjects will complete 48 such trials, which will take approximately 1 hour. Infrared Emitting Diodes will be placed on the subject's index finger, thumb, and wrist, as well across their chest.

8. Does the project as described above expose subjects to any risk of:

		YES	NO
(i)	**Physical stress**	___	X
(ii)	**Psychological stress**	___	X
(iii)	**Harm from electrical or mechanical devices**	___	X

If YES to (i) or (ii), a Subject Consent Form must be used that identifies such risks and offsetting benefits, and a copy of the Experimental protocol must be attached to this application (see sample Form #2 and #5).

If YES to (i), a Medical Release Form to be signed by both the subject and his/her physician must be used.

If YES to (iii), the investigator must affirm that the apparatus has been subjected to all appropriate safety tests and that the apparatus will be operated by a suitably trained person.

	YES	NO
9. Does information to be obtained from subjects include information on activities that are or may be in violation of criminal or civil law?	___	X

10. Please place an X here if your study involves human tissue, including blood. If so, you are required to provide evidence of Biosafety Certification from the institution(s) where the research will take place. ______

REQUEST FOR ETHICAL APPROVAL OF RESEARCH

I AGREE

(i) to secure the informed consent of my subjects in their participation of my project;

(ii) to allow subjects to withdraw participation, in part or in full, at any time;

(iii) to maintain in strict confidence the responses of individual subjects;

(iv) to carry out the research strictly in accordance with the proposal and the documents that accompany it, as well as any conditions imposed by the Ethics Review Committee.

(v) to permit my Chair, Director or Dean to observe the conduct of the research and to verify that procedures are followed.

(Signature of Principal Investigator) **(Date)**

(Signature of Faculty Supervisor)* **(Date)**

*** This signature is required only for Principal Investigators who are not SFU faculty members. It ensures conformity to the agreement by all employees of the Faculty Supervisor engaged in this project.**

The information on this form is collected under the general authority of the University Act (R.S.B.C 1979, c.419) and according to the Terms of Reference of the University Research Ethics Review Committee. This information is directly related to and needed for the review of research ethics applications and will be used to review and make decisions about applications, monitor compliance, and generate lists of approved projects from an electronic database. If you have any questions about the collection and use of this information, contact the Secretary of the University Research Ethics Review Committee at 291-4370.

FORM #2

SIMON FRASER UNIVERSITY

INFORMED CONSENT BY SUBJECTS TO PARTICIPATE IN A RESEARCH PROJECT OR EXPERIMENT

The University and those conducting this project subscribe to the ethical conduct of research and to the protection at all times of the interests, comfort, and safety of subjects. This form and the information it contains are given to you for your own protection and full understanding of the procedures. Your signature on this form will signify that you have received a document which describes the procedures, and possible benefits of this research project, that you have received an adequate opportunity to consider the information in the document, and that you voluntarily agree to participate in the project.

Having been asked by Chris Bertram of the School of Kinesiology of Simon Fraser University to participate in a research project experiment, I have read the procedures specified in the document. "Information Sheet for Subjects" prior to giving my consent to participate in this experiment.

I understand the procedures to be used in this experiment and that there are no personal **risks** to me in taking part. I understand that by participating I will gain no favors, and I understand that I may withdraw my participation in this experiment at any time. Should I decline to participate or withdraw from the experiment, I understand that I will not be penalized in any way.

I also understand that I may address any *questions or queries* I may have about the experiment to the researcher named above, Chris Bertram, or to the Supervisor of the experiment, Dr. Ron Marteniuk. I also understand that I may register any *complaint* I might have about the experiment with the Director of the School of Kinesiology, SFU, Dr. John Dickinson (291-3497).

I may obtain copies of the results of this study, upon its completion, by contacting:
Chris Bertram or Dr. Ron Marteniuk in the Human Motor Systems lab (K8600; phone number: 291-5794).
I have been informed that the research material will be held confidential by the Principal Investigator.

I agree to participate by being instrumented with footswitches and IREDs, then repeatedly walking in a straight line and on command to grasp, transport, and place a full cup on a target as described in the document referred to above, for a period of approximately 1 –1.5 hours at the Human Motor Systems Laboratory (K8600) in the School of Kinesiology at Simon Fraser University. I am not uncomfortable with performing this task.

NAME (please type or print legibly): ______________________________

ADDRESS: ____

____

SIGNATURE: __________________ **WITNESS:** __________________

DATE: ____________________

FORM #3

SIMON FRASER UNIVERSITY

INFORMED CONSENT FOR MINORS AND CAPTIVE AND DEPENDENT POPULATIONS BY PARENT, GUARDIAN AND/OR OTHER APPROPRIATE AUTHORITY TO PARTICIPATE IN A RESEARCH PROJECT OR EXPERIMENT

The University and those conducting this project subscribe to the ethical conduct of research and to the protection at all times of the interests, comfort, and safety of subjects. This form and the information it contains are given to you for your own protection and full understanding of the procedures, **risks [PRINCIPAL INVESTIGATOR MUST SPECIFY THE PERSONAL RISKS AND BENEFITS, EITHER ON THIS CONSENT FORM OR ON THE INFORMATION SHEET FOR SUBJECTS (FORM #5), OF THE PROPOSED RESEARCH].** Your signature on this form will signify that you have received a document which describes the procedures, possible risks, and benefits of this research project, that you have received an adequate opportunity to consider the information in the document, and that you voluntarily agree to participate in the project.

As (parent/teacher/doctor/etc.)____________________of (name of child/patient/-other)____, I consent to the above-named engaging in the procedures specified in the document titled:___________________

____

to be carried out in the following place(s) **[WHERE PROCEDURES WILL BE CARRIED OUT]**:____
at the following time(s):____

in a research project supervised by:____
of:____

I certify that I understand the procedures to be used and have fully explained them to (name of child/patient/other):____

In particular, the subject knows the risks involved in taking part. The subject also knows that he/she has the right to withdraw from the project at any time. Any complaint about the experiment may be brought to the chief researcher named above or to ________________
______________________Chair/Director/Dean,____________________Dept./-School/Faculty, Simon Fraser University.

I may obtain a copy of the results of this study, upon its completion, by contacting:

____

NAME (please print): ____
ADDRESS: ____
____

SIGNATURE:____________________**WITNESS:**__________________

DATE: _______________

ONCE SIGNED, A COPY OF THIS CONSENT FORM AND A SUBJECT FEEDBACK FORM SHOULD BE PROVIDED TO YOU.

FORM #4

SIMON FRASER UNIVERSITY
UNIVERSITY RESEARCH ETHICS REVIEW COMMITTEE

SUBJECT FEEDBACK FORM

Completion of this form is **OPTIONAL**, and is not a requirement of participation in the project. However, if you have served as a subject in a project and would care to comment on the procedures involved, you may complete the following form and send it to the Chair, University Research Ethics Review Committee. All information received will be treated in a strictly confidential manner.

Name of Principal Investigator: **Chris Bertram**

Title of Project:
Co-ordination during a combined locomotion/ prehension task.

Dept./School/Faculty: ______________________________

Did you sign an Informed Consent Form before participating in the project? ____

Were there significant deviations from the originally stated procedures? _______

I wish to comment on my involvement in the above project which took place:

____

(Date) (Place) (Time)

Comments: ____

____

____

____

____

____

Completion of this section is optional

Your name: ____

Address: ____

Telephone: (w)______________________ (h)____________________

This form should be sent to the Chair, University Research Ethics Review Committee, c/o Office of the Vice-President, Research, Simon Fraser University, Burnaby, BC, V5A 1S6.

FORM #5

SIMON FRASER UNIVERSITY

INFORMATION SHEET FOR SUBJECTS

This form describes the proposed tests involving physical, psychological, or any other invasive testing.

Title of Project: Coordination during a combined locomotion/prehension task.

As a subject you will be instrumented with a number of sensors. First, sensors that detect pressure, called footswitches, will be inserted into your shoes. Second, six Infrared Emitting Diodes (IREDs) will be placed on your body. There will be three placed on a velcro band that will be strapped around your chest, and there will be one each on your wrist, thumbnail, and index fingernail of your right hand. These IREDs emit pulses of infrared light which can be detected by the OPTOTRAK ™ 3-D motion analysis camera system mounted in the corner of the room, allowing us to track the movements of your body as you perform the task.

Your task will be to walk in a straight path approximately 2m to a table that is placed parallel to your walking path, pick up a full cup, transport it to a target located either 15, 30, or 45 cm away, place it on the target, then continue walking for about 1.5m until you reach the finish line. You will complete this task 60 times, which should take approximately 1 hour. The cup which you transport may be covered by a lid or uncovered. The cup grasp, transport, and place task is to be completed while you continue to walk along the specified path; it should be performed without interruption to your walking.

You will be allowed to walk at our own pace. You will begin each trial standing behind the start line and will begin walking when the experimenter has said "ready go". You will have a few practice trials to get comfortable with the task.

There are no risks involved. There are no direct benefits to you; however, the results of this research may contribute to the knowledge base in the areas of Human Motor Control and Motor Coordination.

Please ask any questions you may have of the experimenter to ensure that there is full understanding of the task.

FORM #6

SIMON FRASER UNIVERSITY

SUPPLEMENTAL CHECKLIST FOR RESEARCH PROPOSED BY A PERSON WHO IS NOT AN SFU FACULTY MEMBER

ATTACH THE COMPLETED SUPPLEMENTAL CHECKLIST TO YOUR REQUEST FOR ETHICAL APPROVAL (FORM #1). (NOTE: Supplemental Checklist is adapted from a checklist used by the Psychology Department, SFU.)

Name of Principal Investigator (please print): Chris Bertram

Name of Co-Investigator(s) (if applicable): Dr. Ron Marteniuk

Title of Project: Coordination during a combined locomotion/prehension task.

Number and title of course (if applicable) :N/A

Name of Instructor, Supervisor, or TA: N/A

QUESTIONS: Please respond to the following questions by **circling** the appropriate answer. (If there is any doubt as to how to answer the questions below, please circle the underlined response.)

1. Will persons 18 years or younger be involved as subjects in your research? YES NO
2. Will persons in the employ of Simon Fraser University be involved as subjects in your research? YES NO
3. Will the subjects be informed of the nature of their involvement in the collection of data and of all features of the research that reasonably might be expected to influence willingness to participate? YES NO
4. Will the subjects be told that they can discontinue their participation at any time? YES NO
5. Does the study involve concealment from and/or deception of the subjects? YES NO
6. Will deception be used in order to obtain agreement to participate? YES NO
7. Will the participants in your study be aware that they are subjects? YES NO
8. Will subjects or their guardians be asked to sign Consent Forms? YES NO
9. Will information of your subjects be obtained from third parties? YES NO

10. Are you and/or your associate(s) in a position of power vis-a-vis the subjects? YES NO

11. Is any coercion exerted upon subjects to participate? YES NO

12. Is confidentiality of the subject's identity positively ensured? YES NO

13. In cases where there is a possibility that the subject's identity can be deduced by someone other than the investigator, will the participant's right to withdraw his/her data be respected? YES NO

14. Will the investigator fulfill all the promises made to the subjects? Y YES NO

15. Does the study involve physical stress (or the subject's expectation thereof), such as might result from heat, noise, electric shock, pain sleep loss, deprivation of food and drink, drugs, alcohol? YES NO

16. Does the study involve the induction of mental discomfort in the subject (examples: fear, anxiety, loss of self-esteem, shame, guilt, embarrassment, becoming aware of personal weaknesses)? YES NO

17. Will all necessary measures be taken to protect the physical safety of the subjects (from dangers such as faulty electrical equipment, poor grounding, lack of oxygen, falls, traffic and industrial accidents, the possibility of hearing or visions loss, and so forth)? YES NO

18. Does the study involve subjects who are legally or otherwise not in a position to give their valid consent to participate(examples: children, prison inmates, mental patients)? YES NO

19. Will non-coded information obtained on individual subjects be disclosed to third parties? YES NO

20. Could publication of the research possibly interfere with strict confidentiality? YES NO

21. Could publication of the results possibly harm the subject either directly or through identification with his/her membership group? YES NO

22. Are there other aspects of this study that may interfere with the protection of the well-being and dignity of the subjects? YES NO

23. Will the experimenter make all efforts to ensure a normal human relationship between subject(s) and investigator after the collection of data has been terminated? YES NO

24. In cases in which a subject is dissatisfied or complains about the research procedures, will the investigator explain to the subject that he/she may express his/her feelings to the Chair or Director of the Department or School or Dean of the Faculty?

YES NO

25. Will the investigator dispose of the data, once the study is completed, in a way that will safeguard the subject's right to confidentiality? YES NO

THIS SUPPLEMENTAL CHECKLIST SUBMITTED BY______________________________
(Signature of Principal Investigator)

ON__________________________.
(Date)

APPROVED:

________________________________Instructor/Supervisor/TA **(circle one)**
(Signature)

ON ____________________________.