BALANCE CONTROL OF EXTERNALLY-TRIGGERED
AND SELF-INITIATED REACHING MOVEMENTS IN
HEALTHY INDIVIDUALS

By Joe Chien-Ming Lin

A thesis submitted in conformity with the requirements
For the degree of Master of Science
Graduate Department of Physiology
University of Toronto

© Copyright by Joe Chien-Ming Lin 1999
The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

0-612-45563-7
Balance Control of Externally-Triggered and Self-Initiated Reaching Movements in Healthy Individuals

Master of Science, 1998
Joe Chien Ming Lin
Department of Physiology, University of Toronto

Abstract

The kinematic properties, postural electromyographic (EMG) profiles and ground reaction forces were characterized in the context of a visual reaching task in standing and sitting body positions to address the question: does the center of pressure (COP) excursion and the underlining postural muscle activation pattern relative to the onset of the primary mover (anterior deltoid) differ if a rapid reaching movement is externally-triggered (EX) or self-initiated (SI)? With the same motor performance as measured by peak wrist velocity, differences seen in the spatial and temporal characteristics of the distal lower limb muscle activity (earlier tibialis anterior [TA] onset, smaller onset magnitude for SI) and COP excursion (earlier onset, and larger medial-lateral [ML] displacement in SI) were due to the triggering conditions and not to the characteristics of the focal reaching velocity. An increase in the ML COP excursion and a decrease in the AP COP excursion in the non-constrained SI condition in both standing and sitting positions would favor the view that the ML excursion is more likely to be the balance adjustment and the AP excursion is associated with the reach. Differences in lower extremity EMG pattern and COP excursion between SI and EX reaches are direction specific or context dependent. Larger differences were observed in the reaches that required shifting of center of mass across midline to the contralateral side in the standing position. As expected, postural control during a dynamic reaching movement in the sitting position is different from the standing position. Amplitude of COP displacement and the lower extremity EMG pattern was significantly smaller in the sitting position than in the standing position. These findings suggest that SI and EX might be associated with two separate control mechanisms that function in parallel and vary according to the context of the task. Alternatively, these differences could be explained by findings similar to those of Romo and Schultz (1992) where primate upper limb movements under the two triggering conditions involved different anatomical structures.
ACKNOWLEDGEMENTS

As I think in retrospect twenty months ago when I first started this project with no substantial scope, I feel extremely grateful to all the people for their generous support, suggestions, and mentorship over the course of my studies. I also like to take this opportunity to thank all the subjects who participated in the tedious experiments, and for their collaboration and patience in making this project possible.

I would especially like to thank Dr. W. MacKay and Dr. W. McIlroy (members of my thesis committee) for their constant guidance and feedback in the development of my experiments. Their expertise in neuroscience research has been invaluable in the evolution of my critical thinking. In particular, many thanks to Bill for his time and efforts in programming during the stage of data collection and analysis. I wish to thank, as well, Chanh Diep (lab technologist) for his technical advice and assistance in coordinating the various facets of the experiments.

Then, of course, I like to extend heartfelt appreciation to my supervisor, Prof. Molly Verrier, whose enthusiasm, guidance, and friendship have affected me most – from the first day of my M.Sc. program to the completion of my study. In those final hours of last-minute changes, she laboured to carefully review my manuscript far into the night, after full days spent running the Department. This project could never have come into being without her constant encouragement and attention to my concerns. Thanks, Molly!

Special thanks to my parents for their support and their confidence in me!

And last but not least, special thanks to my girlfriend, Joyce, for her unconditional love and belief in me.
# TABLE OF CONTENTS

ABSTRACT .............................................................................................................. ii
ACKNOWLEDGEMENTS ....................................................................................... iii
TABLE OF CONTENTS ......................................................................................... iv
LIST OF TABLES .................................................................................................. vi
LIST OF FIGURES ............................................................................................... vii
DEFINITIONS ........................................................................................................ ix
LIST OF ABBREVIATIONS ................................................................................... x

INSTRUMENT SETUP: ............................................................................................ x
TASKS: .................................................................................................................. x
ELECTROMYOGRAPHY MEASUREMENTS: ....................................................... xi

INTRODUCTION AND RESEARCH QUESTION ................................................. 1
1.1 HYPOTHESIS .................................................................................................... 5

REVIEW OF LITERATURE .................................................................................... 6
2.1 EQUILIBRIUM CONTROL OF MOVEMENT ............................................... 6
  2.1.1 Feed-forward and Feed-back Control of Movement ............................ 6
  2.1.2 Anticipatory Postural Adjustments ....................................................... 8
  2.1.3 Context Dependence of CNS Control of Movement ......................... 9
  2.1.4 SI and EX Movement ........................................................................... 10
2.2 GOAL DIRECTED REACHING .................................................................... 14
  2.2.1 Visuomotor Coordination of Goal-Directed Reaching ....................... 16
  2.2.2 Goal-Directed Reaching In Sitting ...................................................... 19

METHODOLOGY ................................................................................................... 22
3.1 SUBJECTS ...................................................................................................... 22
3.2 EXPERIMENTAL PARADIGM ................................................................... 22
3.3 DATA COLLECTION / RECORDING SYSTEM ........................................... 27
  3.3.1 Kinematics: ............................................................................................ 27
  3.3.2 EMG: ..................................................................................................... 27
  3.3.3 Kinetics/Ground Reaction Forces: ....................................................... 28
3.4 DATA ANALYSIS .......................................................................................... 28
RESULTS .................................................................................................................. 32
4.1 CHARACTERISTICS OF MID-SAGITTAL TARGET REACH: ........................................ 32
4.2 MOTOR PERFORMANCE ......................................................................................... 36
4.3 STAND-REACH: EMG AND COP ANALYSIS ............................................................. 40
  4.3.1 EMG analysis .................................................................................................... 40
  4.3.2 COP Excursion – Relative latency and magnitude ............................................. 43
4.4 SIT-REACH: EMG AND COP ANALYSIS ............................................................... 54
  4.4.1 A Representative Example of Characteristics of mid-sagittal Target Reaches: 54
  4.4.2 EMG analysis: .................................................................................................. 54
  4.4.3 COP Excursion – Relative latency and magnitude ............................................. 55

DISCUSSION .............................................................................................................. 65
5.1 FOCAL MOVEMENT PROPERTIES IN STANDING AND SITTING ............................ 65
5.2 COP EXCURSION AND EMG PROFILE .................................................................. 68
5.3 “SELF-INITIATED” PARADIGMS ........................................................................... 68
5.4 SITTING DOES NOT EQUAL STANDING ............................................................... 74
5.5 CONCLUSION ........................................................................................................ 75

SUMMARY AND CONCLUSIONS .............................................................................. 77

ISSUES FOR FURTHER CONSIDERATION ................................................................... 80
6.1 EXPERIMENTAL LIMITATION .............................................................................. 80
6.2 PHYSIOLOGICAL CONSIDERATIONS .................................................................... 80

REFERENCES ............................................................................................................. 82

APPENDIX (I) : SUBJECT CONSENT FORM AND INFORMATION SHEET 89

APPENDIX (II) : RELATIVE EMG ONSET TIME (TO DELTOID) AND 100 MSECOND ONSET MAGNITUDE ................................................................................. 94

APPENDIX (III) : RELATIVE ONSET AND PEAK TIMES OF COP EXCURSION ................. 103

APPENDIX (IV) : SEGMENTAL COP EXCURSION AMPLITUDE ................................. 112

APPENDIX (V) : SUMMARY OF EXPERIMENTAL RESULTS ..................................... 121
LIST OF TABLES

Table 1: Subjects .................................................................................................................. 22
Table 2: Experimental Conditions, Tasks, and Duration of Collection Period ............... 26
Table 3: Summary of Lower Extremity EMG for Stand-Reach Tasks .................................. 41
Table 4: Comparison of the Latency of SI and EX COP Excursion for Stand-Reach Tasks 44
Table 5: AP COP Onset Time for Stand-Reach Tasks .......................................................... 44
Table 6: ML COP Onset Time for Stand-Reach Tasks ......................................................... 44
Table 7: Peaks of COP Excursion for Stand-Reach Tasks .................................................. 46
Table 8: P value of three-way ANOVA for the Comparison between Conditions, Target Location, and Speed in the Standing Position .......................................................... 47
Table 9: P value of the two-way ANOVA for the Comparison between Conditions, Target Location, for Fast Speed Reaches in the Standing Position, a Supplementary Comparison for non-significance in Table 8 .......................................................... 47
Table 10: Comparison of COP Amplitude between EX and SI Stand-Reach Tasks .......... 48
Table 11: Summary of Lower Extremity EMG during Reaching while Sitting .................. 56
Table 12: Comparison of the Latency of SI and EX COP Excursion for Sit-Reach Tasks . 56
Table 13: AP COP Onset Time for Sit-Reach Tasks ............................................................ 56
Table 14: ML COP Onset Time for Sit-Reach Tasks ............................................................ 56
Table 15: Comparison of COP Amplitude between EX and SI Sit-Reach Tasks .......... 59
Table 16: Peaks of COP Excursion for Sit-Reach Tasks .................................................... 59
Table 17: P value of three-way ANOVA for the comparison between Conditions, Target Locations, and Speed in the Sitting Position .......................................................... 60
LIST OF FIGURES

Figure 3-1: Data collection and experimental setup for standing model ......................................................... 23
Figure 3-2: Data collection and experimental setup for sitting model ............................................................. 24
Figure 3-3: Independent measurements and data quantification of wrist kinematics, EMG, and COP excursion ............................................................................................................................... 29
Figure 4-1a: A representative example of the characteristics of EMGs, kinematics during a mid-sagittal contralateral target reach at fast speed ............................................................... 33
Figure 4-1b: A representative example of pattern of postural EMGs during med-sagittal reach at fast speed ........................................................................................................................................ 34
Figure 4-2: A representative example of the characteristics of COP excursion during a mid-sagittal target reach at fast speed .................................................................................................. 35
Figure 4-3: Peak wrist velocities for all tasks (mid-sagital target, contralateral target, fast and slow) and conditions (SI and EX) .................................................................................................. 37
Figure 4-4: Duration of the acceleration phase (time between movement onset to peak wrist velocity) ....................................................................................................................................................... 38
Figure 4-5: Duration of the deceleration phase (time between peak wrist velocity to target acquisition) ............................................................................................................................................... 38
Figure 4-6: Coupling of wrist and shoulder movement during reaches: difference in onset time of movement ...................................................................................................................................................... 39
Figure 4-7: EX vs. SI mid-sagittal target reach at fast speed: relative EMG onset time (to anterior deltoid) and the 100 msecond EMG onset magnitude ........................................................................ 42
Figure 4-8: EX vs. SI mid-sagittal target reach at fast speed: relative latency of COP excursion ........................................................................................................................................................................ 45
Figure 4-9: EX vs. SI mid-sagittal target reach at fast speed – segmental amplitude of AP COP and ML COP excursion ............................................................................................................................. 49
Figure 4-10: Comparison between EX and SI conditions for averaged maximum COP displacement during Stand-Reach tasks, a regression interpretation ........................................................................... 51
Figure 4-11: Averaged peak AP COP versus ML COP during component (I) and component (II) COP excursion for all Stand-Reach tasks (middle-sagittal target, contralateral target, fast and slow speeds) .................................................................................................................. 53
Figure 4-12: A representative example of the characteristics of mid-sagittal target reach while sitting ................................................................. 57

Figure 4-13: Mid-sagittal target reach at fast speed: relative latency of COP excursion .... 61

Figure 4-14: EX vs. SI mid-sagittal target reach at fast speed while sitting - segmental amplitude of AP COP and ML COP excursion ................................................................. 61

Figure 4-15: Comparison between EX and SI conditions for averaged peak COP excursion during Stand-Reach tasks, a regresional interpretation .................. 63

Figure 4-16: Averaged peak AP COP versus ML COP during component (I) and component (II) COP excursion for all Sit-Reach tasks (mid-sagittal target, contralateral target, fast and slow speeds) ................................................................. 64

Figure 5-1: Onset of preparatory adjustments as measured by the onset of the ipsilateral TA (with respect to DELT) for the Stand-Reach tasks (MTf, MTs, CTf, CTs) .......... 69
DEFINITIONS:

- **Postural Control:**
  Postural control can be defined as the process by which the central nervous system (CNS) generates the patterns of muscle activity required to regulate the relationship between the COP and the base of support (BOS) during a movement.

- **Behavioural Condition:**
  Behavioural condition is referred to as the ways that a dynamic movement is triggered. 1.) Self-Initiated reaching, and 2.) Externally-Triggered reaching

- **Stability:**
  Postural stability is defined as the ability to maintain the position of the body, and specifically, the center of body mass (COM), within specific boundaries of space. Thus it is referred to as the control of COM motion via generation of torque at the joints of the supporting leg or legs and trunk.

- **Equilibrium or Balance:**
  The term equilibrium or balance for the purpose of this study is used interchangeably with stability. When referring to the control of the movement in the upper extremity, the term equilibrium is often used and when referring to the control of the posture, the term balance is used.

- **Anticipatory Postural Adjustment:**
  Anticipatory postural adjustments (APAs) have been characterized by the feed forward postural changes that occur prior to the onset of focal movement to prevent equilibrium disturbances associated with motor performance from taking place. APAs have further been defined as the anticipatory forces generated in the direction that is different from the focal movement.

- **Preparatory Postural Adjustment:**
  Postural adjustments that occur in the same direction as the focal movement may contribute not only to the stability but also to the motor performance of the focal movement. These postural changes are often termed 'preparatory postural adjustments' to avoid confusion with APA.
LIST OF ABBREVIATIONS

Conditions:
EX Externally-triggered condition which is defined by the light in the context of this experiment
SI Self-uninitiated condition which is without the illumination of the light

Parameters:
GRF Ground Reaction Forces
BOS Base of Support; The area of the body that contacts the environment and thereby allows supporting ground reaction forces to be generated. To maintain stable upright stance (without stepping or grasping), the center of mass of the body must remain within the limits of the base of support defined by the feet.
COP Center of Pressure; the point on the base of support at which the ground reaction forces can be considered to act. The displacement of the center of pressure can be used as a biomechanical measure of the stabilizing postural reactions.
COM Center of Mass; The point in space at which the mass of the body can be considered to be located for purposes of analyzing the forces acting on the body. Also known as the center of gravity, because the gravitational force due to the weight of the body also acts through this point.
EMG Electromyography

Instrument Setup:
LED Light emitting diode
FS Finger switch; the switch the finger depresses before execution of movement
T1 Mid-sagittal target to the reaching arm
T2 Contralateral target to the reaching arm

Tasks:
MTf Mid-sagittal target reach at fast speed while standing
MTs Mid-sagittal target reach at slow speed while standing
CTf Contralateral target reach at fast speed while standing
CTs Contralateral target reach at slow speed while standing
SMTf Mid-sagittal target reach at fast speed while sitting
SMTs Mid-sagittal target reach at slow speed while sitting
SCTf  Contralateral target reach at fast speed while sitting
SCTs  Contralateral target reach at slow speed while sitting

Electromyography Measurements:
PS (i / c)  Erector spinae muscle (ipsilateral / contralateral)
DELT  Deltoid muscle (specifically, anterior fiber)
RF (i / c)  Rectus femoris (ipsilateral / contralateral)
BF (i / c)  Biceps femoris muscle (ipsilateral / contralateral)
TA (i / c)  Tibialis anterior muscle (ipsilateral / contralateral)
med-G (i / c)  Medial gastrocnemius muscle (ipsilateral / contralateral)
S (i / c)  Soleus muscle (ipsilateral / contralateral)

Measurements:
RT  Reaction time
MT  Movement time
AP  Anterior-posterior direction
ML  Medial-lateral direction

Component I COP
  Defined temporally from the onset of the COP excursion to the peak of excursion
  in the backward (AP) and 'rightward' (ML) directions

Component II COP
  Defined temporally from the first peak of COP excursion to second peak of COP
  excursion in the forward (AP) and 'leftward' (ML) directions

Peak COP (I)
  Maximum COP displacement in component I of the AP COP (backward) and the
  ML COP (away from the target)

Peak COP (II)
  Maximum COP displacement in component II of the AP COP (forward) and the
  ML COP (toward the target)

Fx  The component of the resulting ground reaction force that acts at the COP and
  accelerates the total body center of mass in the anterior-posterior direction

Fy  The component of the resulting ground reaction force that acts at the COP and
  accelerates the total body center of mass in the medial-lateral direction
Fz The component of the resulting ground reaction force that acts at the COP and accelerates the total body center of mass in the superior-inferior direction
Mx Moment around the anterior-posterior direction
My Moment around the medial-lateral direction
Mz Moment around the vertical direction
S.D. Standard deviation
S.E.M. Standard error of the means
N Newton, unit of measure of the ground reaction forces
1 Introduction and Research Question

This research examines how external or internal stimuli affect the central commands for postural adjustments during an upper extremity movement, like goal-directed reaching. The purpose of this work is to examine the postural adjustments during reaches that require excursion of center of mass (COM) to the edge of the base of support under externally-triggered and self-initiated conditions in both standing and sitting in normal subjects and to seek applicability for studies of stroke patients in the future.

Postural control has been classically defined as the ability to control equilibrium by maintaining or returning the vertical projection of the body, COM within the base of support (Horak et al., 1984; Shumway-Cook et al., 1988; Frank and Eral, 1990, Winter et al., 1990; Patla et al., 1992). However, the stability achieved through postural control does not imply that it is a static process, but rather, a series of adjustments that operate continuously on both a feed forward and a feed back basis. Changing the location of the COM occurs by generating contractions in appropriate muscles (Horak et al., 1984; Massion, 1992; Aruin and Latash, 1995; Benvenuti et al., 1997). These muscular contractions generate forces that function to keep the COM within the base of support. The ability to execute skilled movements and move about with safety depends on executing appropriate postural adjustments to counteract perturbations introduced by the moving body segments (Frank and Eral, 1990; Winter et al., 1990). Reaching movement is carried out everyday in different contexts. The interaction between postural activity and a reaching movement is particularly important to study because reaching is an intentional movement that allows for the study of planned motor responses. Intentional reaching movements whether cued or self-initiated require the execution of appropriate postural strategies for equilibrium maintenance. However, whether the "internally" initiated postural consequences are the same as the "externally" triggered postural consequences is still unclear. The basic intention of this study is thus to alter the conditions (externally-triggered versus self-initiated) under which the focal movements are initiated in such a way that motor control strategies used to regulate the posture for the two strategies can be distinguished. The kinematic properties, postural EMG profiles and ground reaction forces
are the parameters of postural control that need to be characterized to address the effect of external cue or internal cue on postural control during rapid reaching movements.

Leg and trunk muscles are active in association with fast voluntary arm movements in standing (Friedli et al., 1984, 1988; Horak et al., 1984; Benvenuti et al., 1997). This postural muscle activity associated with arm movement has several characteristic features. EMG activity in leg and trunk muscles precedes that of the primary mover of the displaced segment (Belenkii et al., 1967; Horak et al., 1984). Studies implicating postural adjustments as an essential component of voluntary or intentional upper extremity movement were first conducted by Belenkii et al. (1967), who postulated that postural adjustments are necessary to minimize the disruption of equilibrium caused by upper extremity movements. It was revealed that postural muscle activation occurred prior to a voluntary movement of the upper limbs. Belenkii et al. (1967) addressed these as anticipatory postural adjustments. An anticipatory postural adjustment consists of postural activity that begins immediately prior to or concurrent with the onset of a voluntary movement and serves to minimize the potential instability caused by that movement (Horak et al., 1984; Massion, 1992). Both anticipatory and concurrent postural adjustments have been documented during freestanding upper extremity intentional movement (Bouisset and Zattara, 1981, 1987; Friedli, 1984, 1988; Horak et al., 1984; Woollacott et al., 1984; Smith, 1993; Benvenuti et al., 1997) and in platform perturbation studies (Maki and Macllroy, 1996; Gantchev and Dimitrova, 1996). The spatial and temporal characteristics of postural adjustments have been reported to be reproducible within and across normal subjects and highly variable in patients with neuropathology patients (Horak et al., 1984; Massion, 1992; Smith, 1993; Latash et al., 1996). The ability to compensate in anticipation for such perturbations is crucial, especially in the neurological disordered population who are at increased risk of falling, i.e. Parkinson's disease, cerebellar disease, and stroke (Berg et al., 1989; Maki et al., 1994). It has been documented in a rapid arm flexion study, that stroke patients who have no anticipatory lower extremity muscle activation have lower peak arm acceleration and a low Balance Score (Smith, 1993; Stevenson and Garland, 1996). In previous studies on postural control during reaches in post stroke patients in our laboratory, subjects made unilateral rapid arm reaches to a target placed at the edge of their base of support. Furthermore, it has been shown that lack of anticipatory postural muscle
activation is correlated with lack of center of pressure excursion in stroke patients (Verrier et al., 1997).

Although postural control of goal-directed reaching movements has been studied extensively since Belenki in 1967, most theories on control of posture and control of movement are based on human and animal experiments under the externally-triggered conditions (light, sound, and verbal instruction). Movement can be internally initiated (self-initiated) or externally initiated (triggered by events from the outer world). In the first case, we speak of actions that we perform in the absence of an external cue; in the later case we speak of reactions to stimuli from the environment. However, not many studies have determined the difference in central nervous system (CNS) control of movement between externally-triggered conditions and self-initiated conditions despite the fact that externally-triggered and self-initiated movement involve different functional anatomy or different neural-networks. Evidence from animal and human studies has suggested that different cortical regions are involved for externally-triggered movement and for self-initiated movement (Eccles, 1982; Goldberg, 1985; Passingham et al., 1993; Romo and Schultz, 1992; Jahanshahi et al., 1995; Lang, 1994; Deecke, 1996). There is more supplementary motor area (SMA) activity when the movement is initiated by the subjects themselves than when it is initiated (triggered) by an external cue (Passingham et al., 1993). Well-controlled bilateral lesions of SMA in monkey lead to impairments in self-generated movements requiring an internal representation of the target (Passingham et al., 1993). If the neural control for the externally-triggered movement is different from self-initiated movement (based on the fact that they involve different functional anatomy), theoretically, lesions of different brain structures should result in unique motor deficits.

There are two rationales for investigating the differences in movement control between the externally-triggered condition and self-initiated condition at the behavioral level with human subjects, especially stroke patients. One is to identify the relationship between site of lesion and the recovery of postural control. Since animal studies have shown that different brain structures are involved, investigation of self-initiated and externally-triggered movement could provide ways to examine the relationship between the site of lesion and the impairment in control of movement or movement initiation. The other rationale is to improve the understanding of clinical stroke rehabilitation strategies.
Effective rehabilitative strategies to improve motor or functional recovery in patients with hemiparesis depend on the knowledge of the underlying mechanisms of movement deficits and how they change over the recovery process. The ability to disentangle the different mechanisms for the planning and execution phase of motor acts using paradigms that include externally stimulated tasks and internally generated tasks could be beneficial. Traditionally, therapists are taught to assist the movement by verbal instruction or hands-on assistance during the rehabilitation process of stroke recovery. Is it better to apply the traditional “externally-triggered” way of therapy or is it more beneficial to apply the “self-initiated” or “internally-generated” therapeutic approach to movement re-training or some combination? Questions like this addressed critically and studies that examine the fundamental differences in CNS control of movement between movements that are the externally-triggered and self-initiated will pave the road to answer a difficult question like this. Consequently, studies that examine the difference in postural or balance control of reaching movement could potentially be used to identify the effect of lesion site and the consequent motor deficit, but also could be used as an effective rehabilitation strategy for stroke patients.

The question raised in this study are, how do EX or SI conditions affect the central control of postural adjustment during an upper extremity reaches in healthy individuals in standing and sitting? Specifically, the study is setup to examine whether the center of pressure (COP) excursion and the underlying postural muscle activation relative to the onset of primary mover activity (anterior deltoid) differ if a rapid reaching movement is externally-triggered (EX) or self-initiated (SI).
1.1 Hypothesis

H₁ Differences in the spatial and temporal EMG activity of the lower extremity muscles and COP excursion are due to the effect of cueing (EX versus SI) and not to the focal reaching velocity.

H₂ Earlier onset time of lower extremity EMG activity and COP excursion (relative to deltoid) will reveal that execution of the preparatory postural adjustments is earlier in the SI condition as compared to the EX condition.

H₃ Differences in lower extremity EMG pattern and COP excursion between the EX and SI reaches are directionally specific.

H₄ Differences in the postural control during reaches in the standing position are similar different to those the sitting position.
2 Review of Literature

The purpose of this study is to understand the central nervous system control of movements executed under different behavioral conditions, namely the SI or internally-generated and EX movements. Most of the hypothesis on the control of the planning and the learning of the movement are derived from upper limb models (Levin and Dimov, 1994; Zehr, 1994; Desmurget, 1996). It was not until recently that researchers have tried to investigate the postural component of a reaching movement in the standing position (Horak et al., 1984; Latash et al., 1995) and in the sitting position (Moore et al., 1992; Dean and Shepherd, 1997). In this literature review, the main focus will be on the equilibrium control of movement and the associated postural adjustments with special emphasis on reaching. Context dependency of movement and visual-motor coordination of the goal-directed reaches will also be reviewed to further understand the control of reaching.

2.1 Equilibrium Control of Movement

We carry out numerous movements daily without consciously thinking about them. It is only when we see people with impairments, that we start to wonder how our central nervous system controls simple movements like reaching towards a cup, reacting to a sudden stopping action of the bus by reaching to a handle, or the initiation of stepping or running. Most movements that we carry out have a goal, whether this goal is conscious (like reaching toward a tea cup) or unconscious executed (like reacting to bus stepping or postural sway in quiet standing). These goal-directed movements have three distinct phases: the identification of the goal, the planning of strategies for the movement and the actual execution of the movement and the correction of errors that occur during the course of action. The staging of these three phases is precisely controlled by our central nervous system.

2.1.1 Feed Forward and Feed Back Control of Movement

Movement controlled by the central nervous system relies heavily on two major mechanisms, namely feed forward and feed back control (Rothwell, 1987). Depending on the context of the movement and the information gathered prior to the movement, the plans executed by the CNS may be different, thus generating a different movement (Massion,
1992; Lang, 1994; Latash et al., 1995). Whether these plans are the result of pre-programmed neural-network (hard-wired connection) or precise calculation from new information or the combination of the two remains controversial.

Feed forward and feed back mechanisms are simply two fashionable terms to describe the actions we carry out everyday. For example, while reaching for a cup, we rely on the visual feed forward information and visual and “proprioceptive feed back information” (joint angle, muscle spindle stretch, or even the breeze across the hair on our skin) (Ghez and Sainburg, 1995) to inform us to decelerate our hand and arm so that we can grasp the cup appropriately. In a feed back system, a feed back signal is compared to the reference value, any deviation will be adjusted to re-establish the reference value (Massion, 1992). In a quiet standing situation, stability about a narrow base of support is the reference; any deviation that might threaten the stability of the system could cause a fall. Postural sway during quiet standing is therefore controlled by the feed back mechanism trying to stabilize center of gravity (Desmurget, 1996; Pai et al., 1994). Inability to feed back to the central nervous system (control of the center of gravity above base of support) correctly might quickly translate into a higher risk of falling in the older population. Studies have shown that control of medial-lateral stability will best predict risk of falling and thus should be a major focus in choosing techniques to assess balance and falling risk and in developing interventions to help prevent falls (Berg et al., 1989; Maki et al., 1994; Maki and McIlroy, 1996).

In a reaching task, the distance of the trajectory between initial arm position and the end target position is the reference value first established by the CNS. As described in the equilibrium point hypothesis (Bizzi et al., 1992), it is possible to set muscle parameters so that opposing muscle forces or reflex-induced muscle changes are in equilibrium when a particular limb configuration is achieved. According to one variant of the equilibrium point hypothesis, once the relevant muscle parameters are set, the limb gravitates automatically to the equilibrium configuration, which makes explicit specification of a complete trajectory to the final position necessary. A considerable amount of evidence has been obtained to indirectly support this hypothesis (Bizzi et al., 1992), though there has also been debate about the importance of afferent feed back in realization of the goal position (Latash et al., 1995). If in the middle of the movement, external or internal
position (Latash et al., 1995). If in the middle of the movement, external or internal perturbation creates an error in the arm trajectory, a feedback signal is quickly sent to the somatosensory area of the brain to initiate a series of corrective CNS activity to bring the error trajectory back to the desired path. In a study where there was a constrained arm movement and an un-constrained arm movement between two points in space, authors have shown that the constrained evoked significant forces strongly oriented so as to restore the hand to the unconstrained hand path. In other words, the CNS has calculated the preferred trajectory minimal force output between two points in space and in the situation where perturbation occurs, corrective forces are generated to re-establish the preferred path (Won and Hogan, 1995).

2.1.2 Anticipatory Postural Adjustments

The preferred trajectory of a reaching movement is usually considered the result of the feed forward information integration. A feed forward control system relies on advance information to adjust controlled variables to establish a desirable end point. Numerous studies have tried to examine the feed forward control of movements and associated posture. Most of these studies focused on uncovering the anticipatory postural adjustments (APA) associated with rapid voluntary movements. This phenomena was first introduced by Belenkii in 1967 in order to understand how the postural component is involved in maintaining balance when disturbances are introduced by the voluntary movement of the arm mass. Anticipatory postural adjustments have been characterized by the onset of postural changes that occur prior to the onset of focal movement and that feed forward postural control is associated with movement control, the purpose of which is to minimize the disturbances associated with movement performance (Massion, 1992). Anticipatory postural adjustments have also been documented to exist in forearm flexors during a bimanual load-lifting task (Dufosse et al., 1985; Paulignan et al., 1989; Viallet, 1992). It was observed that during the unloading of the “postural” forearm by a voluntary movement of the subject’s other arm, an anticipatory inhibition of the postural forearm flexors occurred, which was time locked with the onset of biceps contraction in the voluntarily forearm. In platform perturbation studies, sway induced by the unexpected backward movement of the platform triggers a rapid postural response in the gastrocnemius muscle.
that occurs progressively earlier and with high bursting magnitude in repeated trials (Horak et al., 1984; Nashner and McCollum, 1985). Consequently, anticipatory postural adjustments are prevalent strategies used centrally to increase postural stability during movement that vary in contexts. By virtue of its definition to increase stability only, APA have been suggested to be the forces generated in the different direction from the focal movement (Massion, 1992). In the less contrived paradigm such as voluntary reaching with forward lean, movements cannot be divided into stability component (APA) and focal movement component. Therefore, APA should not be confused with preparatory postural adjustments that describe postural changes that may occur in the same direction as the focal movement and thus contribute not only to the stability but also to the motor performance of the focal movement.

Together, these results illustrate an essential feature of postural control; that an individual’s feed forward or anticipatory postural responses are shaped by experience and are context dependent.

2.1.3 Context Dependence of CNS Control of Movement

In order to explore how the CNS controls movement and associated postures in different contexts or experiences, it is necessary to explore the concept of a reference value in a feedback or feed forward system (Massion, 1992). In other words, identification of the controlled goal for each given motor task needs to be established. If one’s goal is to maintain body stability during quiet standing, then the stability of the center of gravity within a narrow base of support in the standing position is the reference value. If the goal of a task requires following specific instructions, then the consequent motor acts are centrally controlled by that reference value. The concept of stabilized reference values for equilibrium control in motor tasks is very important because it is proposed that they are the fundamentals on which the organization of the postural adjustments are currently based. Consequently, reference values are suggested to determine the context dependency of movement control.

It is said that there are two types of control (Massion, 1992). The first consists of maintaining a reference value against the external or the internal world. In a defined three-dimensional space, the reference value can be the position of a given segment such as the
arm, the leg, the trunk or that of the whole body. An example of this type of control is the postural stability during quiet standing where the position of a segment is taken as a reference value and stability during a voluntary movement is provided by the anticipatory adjustment of forearm flexors during a bimanual load-lifting task (Friedli et al., 1984, 1988; Viallet, 1992; Smeets et al., 1995). However, not all equilibrium control of voluntary movement is associated with adjustment to movements that occur prior to the focal task. The second type of control is the displacement along a trajectory of one or several segments or the whole body towards a given goal. Initial posture is broken down before building up a new one. Both reaching and grasping belong to this category. In contrast to perturbation and stepping paradigms where the balance postural component and focal movement can be clearly separated, it is more difficult to separate in voluntary reaching movements. In reaching and grasping, postural adjustments (to stabilize) occur simultaneously with the task (to destabilize) in the same direction. Most of our daily motor acts involve a combination of the two types of control mechanisms to regulate equilibrium or balance. Because every movement is different, a unique combination of these two CNS control mechanisms is thought to be used to generate unique sequences of muscle contractions.

2.1.4 Self-Initiated and Externally-Triggered Movement

Movement can be internally initiated (self-initiated) or externally initiated (triggered by events from the outer world) (Deecke, 1996; Lang, 1994). The first case is often referred to as actions, where movements are performed in the absence of an external cue, out of one’s free will and the latter case is usually refereed to as reactions to stimuli from the environment. Various paradigms have been used to selectively measure the brain activity preceding and accompanying actions and to analyze the interactions between the two states to delineate the functional anatomy of the brain.

A series of studies on subhuman primates with lesions (Romo and Schultz, 1992) and on patients with Parkinson disease (Jahanshahi et al., 1995) have been conducted. These findings suggested that the SMA at the medial surface of area 6 is involved in the internal generation of voluntary movement (self-initiated) (Eccles et al., 1982; Goldberg, 1985; Lang, 1994; Deecke, 1996) and to a lesser extent in the externally-triggered
movements. Human studies have also shown that patients with extensive SMA lesions suffer from a predominant lack of self-initiated (internally initiated), intentional behavioral responses, including limb movements and speech, whereas behavioral reactions to externally stimuli are less impaired (Goldberg, 1985; Talairach and Tournoux, 1993). Well-controlled bilateral lesions of SMA in monkeys led to impairments in self-generated movements requiring an internal representation of the target (Passingham et al., 1993). However, unilateral SMA removal does not result in similar deficits (Brinkman, 1984).

Other lesion studies in monkeys show that while lesions of the primary motor cortex cause weakness of muscles during a movement, lesions of the pre-motor cortex and supplementary motor area (SMA) impair the ability to develop an appropriate strategy for movement. Furthermore, electrophysiological studies investigating the intentional aspect of SI versus EX movement have revealed a potential shift over the SMA and other frontal and parietal cortical areas which preceded by about 1 s the onset of the spontaneously initiated arm muscle activities (Kornhuber and Keeke, 1978). Using fMRI the role of the SMA in the internal representation of movements has also shown that there is an increase in hemodynamic response during the mental rehearsal of complex sequences of finger movements (Roland et al., 1982) and the neuronal activity specifically preceding particular sequences of arm movements (Mushiake et al., 1990).

Although the importance of SMA in internal initiation of movement is well accepted, it is also important to understand how the link between the frontal cortex and other brain structures such as basal ganglia or striatum differ between EX and SI. The different areas of frontal cortex are intimately linked with the basal ganglia through closed neuronal loops (Alexander et al., 1990). In one of these loops, the SMA projects to the striatum, particularly the lateral putamen and dorsolateral caudate (Selemon and Goldman-Rakic, 1985), which then connects, via the globus pallidus and ventroanterior thalamus, back to the cortex at the level of SMA and motor cortex (Schell and Strick, 1984). Thus this loop links two major centers that participate in the internal generation of voluntary movements, the SMA and the basal ganglia. In order to further elucidate the role of cortico-basal ganglia loops in the internal generation of movement, Romo and Schultz (1992) investigated the cellular activity of SMA neurons in the same behavioral contexts and compared them to the cell activity obtained in the striatum using the same monkeys. It was
concluded that in addition to SMA, internally generated preparatory activity may originate outside of the SMA and striatum or may derive from activity reverberating in cortico-basal ganglia loops, possibly in conjunction with other, closely associated cortical and subcortical structures (Romo and Schultz, 1992). These findings favor a conjoint role for SMA and striatum in the internal generation of individual behavioral acts and the preparation of behavioral reactions.

To demonstrate the difference between EX and SI further, cell recordings and lesion studies in monkeys indicate that premotor cortex (PMC) lateral area 6 is crucial when movement selection is based on information given by external cues (Passingham et al., 1993; Lang, 1994). Using positron emission tomography (PET) and movement-related potentials (MRP) using a right index finger tapping paradigm, the underlying functional anatomy of self-initiated and externally-triggered movements were also found to be different with greater activation of the right dorsolateral prefrontal cortex in the self-initiated condition (Jahanshahi et al., 1995). EEG studies also found that the SMA contributes to the early BP (Lang, 1994; Jahanshahi et al., 1995) and the deficit in self-initiated movement in Parkinson’s disease is due to the under-activation of the SMA. In addition, in a review article by Lang (1994), it was further concluded that a certain level of intentional and attentional control seems to be critical for movement related SMA activation.

Single cell recordings (Passingham et al., 1993; Romo and Schultz, 1992), brain EEG recording (Kornhuber et al., 1978), and brain hemodynamic changes during movement studied by using PET (Jahanshahi et al., 1995) and fMRI (Wildgruber et al., 1997) all directly and indirectly infer that the self-initiated movement condition involves different functional anatomy of the brain when compared to the externally-triggered condition. But how do these differences affect human movement control? Can these differences reflect a difference in movement control and the associated postural control as detected at a behavioral level, as measured by the underlying muscle activation patterns, body kinematic, and kinetics during a functional reach. In a study by Benvenuti et al (1997) the latency and duration of electromyography (EMG) and center of pressure (COP) displacement were quantified to compare the anticipatory postural adjustments under self-paced (SI) and reaction time (EX by light) upper arm flexion. They found that with similar
motor performance (measured by focal movement velocity), the phasing (including the order of activation) and duration of anticipatory postural EMG activity and the phasing of COP displacements under certain biomechanical conditions were significantly influenced by the behavioral conditions (Benvenuti et al., 1997). Specifically, latencies of the first posterior peak of the COP to the focal movement were significantly shorter for the externally-triggered movements than the self-initiated condition. That is, COP excursion peaks earlier in SI as compared to EX, referenced to the onset of the focal muscles. EMG data from the same study shows that in the self-initiated movement, burst latencies in the erector spinae and biceps femoris muscles preceded the onset of the activity of the focal muscle, whereas in the externally-triggered movement most bursts occurred coincidentally with or subsequent to the onset of focal muscle discharge. The standing model that examines the anticipatory postural adjustment of the lower extremity musculature was also repeated by weight unloading from extended arms (Aruin and Latash, 1995; Aruin and Latash, 1996). It was found that anticipatory postural adjustments were seen during all SI unloading as changes in the level of activation of postural muscles and in displacements of the center of pressure excursion. Such reaction was absent when the unloading was “triggered” by the experimenter. It is concluded that a self-initiated perturbation is typically associated with APAs, the magnitude of which may be scaled with respect to the magnitude of the motor action used to induce the perturbation.

In a different paradigm which also examines the APAs with self-induced (SI) unloading of weight and EX unloading of weight (time of the unloading is not known to subjects – not a reaction time study) in the sitting position, Jean Massion and his colleagues (1992) asked subjects to maintain flexion of the elbow when a weight placed on their wrist was suddenly removed. The ability to perform this task depended on whether the weight was removed actively (SI) or passively (externally removed by the experimenter). When subjects removed the weight with their free hand, the biceps of the supporting arm relaxed concurrently and without delay as the weight was removed. But if the examiner removed the weight, the subjects could not maintain flexion of the arm, even though they anticipated the removal. Similarly, flexion could not be maintained when the weight was removed passively with an electromechanical device operated by the subject. The biceps relaxed only after a delay, corresponding to a brief simple reaction time following removal of the
weight (Dufosse et al., 1985). Patients with unilateral lesions of the SMA were unable to coordinate muscle contractions of their arms when a weight was placed on the affected arm. Furthermore, subjects invariably responded with a delay to both active (SI) and passive (EX) removal of the weight. Task performance was comparable to the control subjects, however, if the weight was placed on the unaffected arm (ipsilateral to the lesion.)

In conclusion, the neural activity of the brain as measured by single cell recording and functional anatomy using PET, fMRI, EEG and MRP paradigms in both primate and human studies on the control of the upper limb movement support the idea that during the performance of a voluntary movement, SI and EX conditions may involve two separate motor strategies with the self-initiated movement requiring more integrity of the SMA. It becomes important to see if the preparatory postural adjustments that are associated with voluntary upper limb movement are also different for the two types of cueing conditions.

2.2 Goal-Directed Reaching

Reaching is a functional multijoint movement that allows for the exploration of objects in extracorporeal space. Arm movements are the result of complex sensorimotor coordination and involve motion at the shoulder and elbow joints in order to transport the arm in addition to the wrist and fingers (Georgopoulos, 1986; Desmurget, 1996, 1997). All reaching movements involve some sort of goal; thus they are called goal-directed reaches.

It has been repeatedly stated in the literature that the velocity-time profile of the reaching movement is bell-shaped and can be scaled in both the amplitude and time domains (Hollerbach and Flash, 1982; Soechting and Flanders, 1992). Other authors refute the notion that the planning and control of trajectories is simply a scalar adjustment of the base bell-shaped velocity form (Jeannerod et al., 1982, 1987). For example, Soechting and Flanders (1992) found that arm movements to small targets (i.e. a precision target reach) result in a skewed velocity form with peak velocity being achieved earlier in the movement and a prolonged deceleration phase. Similarly, Cole and Abbs (1986) found that movements involved in pointing to targets look very different from those involving grasping an object (Cole and Abbs, 1986). Tasks requiring precision grip (i.e. small objects) have an increased movement time with a disproportionately longer deceleration phase, i.e. a bell shaped curve skewed to the left. In other words, planning and excursion
controlled by the CNS depends on the context and conditions in which the reach is to be performed. And accordingly, the top level of movement planning are unlikely to be singly concerned with the regulation of one kinematic variable.

Studies on the cortical control of limb movements in the monkeys have indicated that there is asymmetry of hemispheric control of movement, that is control of movement by one hemisphere is different than that by the other hemisphere. One hemisphere is able to control the proximal muscles of both limbs; however, the same hemisphere is able to control only the more distal musculature of the contralateral limb (Kuypers, 1978). It seems plausible to suggest that in humans visually guided reaches that require endpoint accuracy may be initiated and controlled by the hemisphere contralateral to the reaching arm (Fisk and Goodale, 1985). If this is true, there is an implication of differential hemispheric specialization in the control of the visually guided reaches. The literature suggests that the left hemisphere plays an important role in the sequential organization of complex motor behaviors, such as articulation, nonverbal oral movements and manual movements (Kimura, 1982). As a result of the left hemisphere's role in the timing and sequencing of movement, it is thought that it may play an important role in control of rapid and accurate reaching movements (Fisk and Goodale, 1985). Although the left hemisphere may be responsible for the sequencing of movements, it is unlikely to play an exclusive role in the efficient planning and execution of visually guided reaching. In fact, the right hemisphere is suggested to specialize in the processing of visuospatial information (Fisk and Goodale, 1985). Nonetheless, it may be the demand for precision in timing of movements in visually guided reaching that has shifted the hand preference (i.e. dominance) from left in primate to right in human (Fisk and Goodale, 1985). In other words, it may be preferable to reach with the right hand in order to optimize the temporal aspect of the reach due to precision.

Regardless of whether the reach was performed with the left or the right, dominant or non-dominant hand, Fisk and Goodale (1985) found that reaches which crossed the body's mid-sagittal axis to a target on the contralateral side were different from those reaches toward targets on the ipsilateral side of the reaching arm. They found that contralateral reaches took longer to complete and had a lower peak velocity than ipsilateral reaches. These findings are in direct conflict with the results found by Smith (1993), where reaches to contralateral targets generated higher peak velocities than reaches to ipsilateral
targets. Such differences could be attributed to possible differences in experimental paradigm.

Despite the discrepancy in the literature regarding the "velocity profile" of the ipsilateral and contralateral reaches, it is generally agreed that the kinematic properties of reaches into contralateral space take longer to initiate and complete than do reaches into ipsilateral space (Fisk and Goodale, 1985; Smith, 1993; Happee, 1993). These findings are also in agreement with the directional specific characteristics of cells in the motor cortex that are reported to tune for direction (Caminiti et al., 1990).

2.2.1 Visuomotor Coordination of Goal-Directed Reaching

Planning of a visually guided goal-directed reaching movement involves a series of visuomotor transformations of extrinsic (target location, hand path, velocity profile), intrinsic (joint angles, muscle length) and dynamic factors (net output forces, muscle activation patterns, joint and muscle torques) (Kalaska et al., 1993; Desmurget, 1997). These transformations in the CNS are essential for the precise coordination of eye, head and arm movements during reaching to targets. Saccades have been shown to lead arm muscle activities by approximately 50 ms in the visually guided reaching for mid-sagittal targets, however, the duration increases slightly for contralateral targets (Jeannerod, 1982, 1987; Fisk and Goodale, 1985). Head movement after the onset of light cue (latency approximately 300 ms) is followed closely by that of the reaching arm. The timing and reproducible nature of the eye-head-arm sequence of events lends support to the notion that the neural commands to the component segments (eye, head, arm) in the context of a visually guided reach are generated in parallel (Jeannerod et al., 1982, 1987) and may be part of a reaching motor program. There is less evidence demonstrating the temporal relationship between posture and eye-head-arm coordination. APAs have been shown to precede activation of the prime mover in the context of a visually guided reaching by as much as 50-100 ms (Massion, 1992). Depending on the tasks studied the latency of the preceding APAs could vary; however, such variability is within the task. When considering a reaching movement in the standing position, the postural component should not be isolated from the well-controlled and coordinated head-eye-arm component. Therefore, activation of the eye, head, posture and finally the arm would be a more
accurate statement regarding the sequence of events preceding a visually guided reaching task.

We move in a three-dimensional world where precise sensory and motor coordination is necessary. Many questions about how sensory information is used to control and coordinate goal-directed movements have been raised. To answer these questions, one must determine how spatial parameters are encoded by the activity of neurons. Central to any spatial description is the concept of a frame of reference. Frame of reference could be retinocentric, i.e., one fixed to the eye. Frames of reference could also be related to the head, to the trunk, and to the earth. Arm movements to a spatial target must utilize sensory information that is initially represented in a different frame of reference from motor command, and the sensory signals that specify target location need to be transformed into motor commands to arm muscles. Thus, the same questions concerning frames of reference and coordinate transformations that we have dealt with for eye, head, and body movements also arise in the study of arm movements. Certainly, one also must not forget that any movement can be generated for different magnitudes of force output. Absolute force is another frame of reference that needs to be considered. In other words, the sensori-motor system needs to transform all possible spatial parameters (head position, arm position and posture position) and non-spatial parameters, forces, in the same frame of reference and context. To understand central processing of information in the sensorimotor system for the control of arm movements into three-dimensional space, one should first identify if neural activity defines a coordinate system. We must first understand how sensory information is encoded at the neuronal level. If such understanding of sensory transformation can be satisfied, it may become possible to describe neural processing in geometric terms, i.e., transformations from one frame of reference to another and transformations between coordinate system within a single frame of reference (Massion, 1992)

Many researchers believe that the advantage of representing information in different parts of the central nervous systems in a common frame of reference might be that the exchange of information is facilitated, thus resulting in less computational time and effort for control of movement. This would be especially true if the same coordinate system in represented in each part.
Evidence has shown that such spatially based frames of reference exist in the central nervous system. There are directional specific encoding neurons in the cortex (Georgopoulos, 1986). There is evidence that neurons in motor cortex, like those in the superior colliculus, encode the direction of movement by population vector code, suggesting that spatial parameters are transformed and represented in neurons of the primary cortex. The observation that flexion and extension of wrist or elbow are associated with the firing of different populations of cortical neurons suggests that there is a muscle like map in the primary motor cortex. However, since individual neurons in the primary motor cortex could potentially influence multiple muscles, the question arises of how the direction of typical multijoint arm movements might be encoded by neurons in the cortex. Georgopoulos and his colleagues (1986) addressed this question by studying how neuronal activity varies when monkeys move a handle to one of several targets arranged around a central starting position. They found that the activity of individual neurons varied with the direction of the movement. Firing pattern is most brisk for movements in a preferred direction, the direction of movement, and neurons fell silent during movements in the opposite direction. Moreover, there is evidence that neurons located within a column of cortex are quite similar, that is, they have similar directional characteristics. However, they also found that the directional tuning of all recorded neurons was, however, surprisingly broad. Individual neurons contribute predominantly to movements in a preferred direction and to a lesser degree to movements in other directions. This suggests that movement in a particular direction may be determined not only by the action of single neurons but by the net action of a large population of neurons. Furthermore, the contributions of each neuron to a movement in a particular direction could be represented as a vector whose length is proportional to the degree of activity during movement in that particular direction. The contributions of individual cells could then be added to produce a population vector. Georgopoulos proposed that the direction of the population vector would determine the direction of movement. Therefore, this experiment has shown that the information of the target location is transformed into motor commands in a spatial fashion at the neuronal level.

It is also suggested that the motor cortical cells have been found to code for the direction of the movement in a way which is dependent on the position of the arm in space.
This further suggests that motor cortical cell activity may be related to the angular displacements of the joints involved in arm movements (Caminiti et al., 1990). The degree to which the movement-related activity of the cell population reflects the dynamic level of representation of movement is not known, i.e. force output (Kalaska and Drew, 1993). If neurons were concerned only with the extrinsic kinematics of the movement such as direction, then the tuning curves as described by Georgopulos et al., 1982, 1986, would reflect the geometry of the target locations (Kalaska and Drew, 1993). However, because of the complexities of multiarticular movements, the direction of the hand displacement during a reach is often not co-linear with the direction of forces required to produce the movement.

Given the proposed nature of the motor cortical cells’ signaling and the observed coupling between motor cortical cell discharge and muscle activation and joint kinematics, it becomes clear that the motor cortex is neither at the highest level of motor control, i.e. as an abstract global planner, or at the lowest level, at the level of the spinal motoneurons and muscles (Kalaska and Drew, 1993). The strongest evidence reveals that it probably lies somewhere in between the two, receiving visuospatial input from neural networks “above” and sending output to structures “below” via other structures. If the motor cortex takes its place in the middle position of the hierarchical planning model for movement execution, the critical focus is on the identity of the structures sitting at the top of the hierarchy and serving as the abstract global planner or modifier for the impending movements. Therefore, using the EX and SI experimental paradigm, one could examine how movement initiation and its associated postural adjustments are controlled differently at a higher level of movement planning execution.

2.2.2 Goal-Directed Reaching In Sitting

Postural control during goal-directed reaches in the standing position have been characterized in normals and stroke patients. It has been shown that there is a stereotypical postural muscle activation pattern during reaches in the standing position in healthy individuals (Smith, 1993). Preparatory muscle activity was observed in anterior distal muscle (tibialis anterior) followed by the anterior proximal muscle (rectus femoris) prior to the onset of the focal muscle during reaching. Posterior muscles are then activated in the
same distal to proximal fashion. Verrier et al. (1997) then reported a high variability in postural EMG activity with no further improvement at three to six months posterior stroke. In order to understand postural motor recovery during upper extremity movement post stroke, investigation must therefore be carried out at early stage. Postural control during goal-directed reaches in the sitting position thus provide ways to examine motor impairment at early stage of the recovery process. Minimal numbers of studies have been carried out to examine postural control during voluntary movement in the sitting position. Moore et al. (1992) using the goal-directed reaching paradigm has reported the onset of deltoid EMG activity precedes the onset of postural muscle (external oblique and paraspinal) EMG activity for seated subjects in contrast to reports of EMG activity onset in the postural muscle in advance of the prime mover in standing subjects who performed a similar task (Horak et al., 1984; Smith, 1993; Verrier et al., 1997). Although the functional recovery of the reach has shown that those patients who received standardized training programs increase speed of reach and distance of reach as compared to the group of patients who did not receive training, the motor recovery of the postural control during reaches in the sitting has not been addressed. The associated postural adjustments during reaches in the sitting position need to be characterized in normal individuals in order to provide a baseline to examine the early stages of the motor recovery process post stroke.

Movement can be internally initiated (SI) or externally initiated (triggered by events from the outer world). Studies of functional anatomy by ways of single cell recordings, brain EEG recording, and brain hemodynamic changes during movements using PET and fMRI all directly and indirectly infer that the SI movement condition involves different functional anatomy of the brain when compared to the EX condition. It has yet to be determined whether these two parallel existing neuronal networks will reflect a difference in postural control. Scientists have recently started to investigate the control mechanism of these two mechanisms. From the unloading experiments, it was found that anticipatory postural adjustments are associated with SI unloading whereas EX unloading are not. “Self-initiation” or “internal-generation” of movement are two unclear terms that are subject to interpretation. Due to the lack of agreement physiologically regarding the definition of “SI” or “internal-generation” of movement, and “externally-triggered” or
“visually-cued” movements the interpretation of distinct differences in their motor control still some caution. The ability to disentangle the difference in mechanisms for the planning and execution of the motor acts under the internally-generated and the externally-generated conditions could be beneficial, especially to the understanding of motor function and motor recovery post-stroke.
3 Methodology

3.1 Subjects

Six young healthy subjects ranging from 19 to 25 years of age (21.2 ± 1.8 [S.D.]) participated in the study. The subjects had no history of neurological disease. The protocol was approved by the internal ethics committee at the University of Toronto, Ontario, Canada (Appendix I).

Table 1: Subject

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>Age</th>
<th>Gender</th>
<th>Hand Dominance</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>23</td>
<td>F</td>
<td>Right</td>
</tr>
<tr>
<td>N2</td>
<td>22</td>
<td>F</td>
<td>Right</td>
</tr>
<tr>
<td>N3</td>
<td>19</td>
<td>M</td>
<td>Right</td>
</tr>
<tr>
<td>N4</td>
<td>19</td>
<td>M</td>
<td>Right</td>
</tr>
<tr>
<td>N5</td>
<td>23</td>
<td>M</td>
<td>Right</td>
</tr>
<tr>
<td>N6</td>
<td>21</td>
<td>F</td>
<td>Right</td>
</tr>
</tbody>
</table>

3.2 Experimental Paradigm

The experimental paradigm was a voluntary reaching movement in the standing and sitting position. Changes in the associated postural muscle activity of the trunk and the lower limbs that may be related to both the focal movement and stability of the body were measured in order to investigate the underlying preparatory postural control as the reaches were carried out. Cue (EX) or non-cue (SI) behavioural conditions were introduced to examine whether the preparatory postural adjustments were altered according to cue presentation.

All subjects were brought to the Restorative Motor Control Laboratory in the Department of Physical Therapy at the University of Toronto. Subjects performed fast reaches to targets by reacting to the illumination of a light or initiating the reaches spontaneously. Subjects performed reaches in two postural states: standing (Figure 3-1), and sitting (Figure 3-2); two speeds: fast and preferred; and two target locations: mid-sagittal and contralateral (60 degrees) from midline of the body.

In the standing model, each subject assumed a comfortable standing position on two force plates with one foot on each plate. Standing position was established by asking subjects to adopt their comfortable standing posture with their eyes closed. In order to
Figure 3-1: Data Collection and Experimental Setup for Standing Model
Figure 3-2: Data Collection and Experimental Setup for Sitting Model
control for the foot position and the width of base of support, foot tracings of the initial
stance assumed by the subjects were obtained. Subjects were asked to adopt the original
foot position on subsequent trials. The position of the medial and lateral malleoli was
documented in order to estimate the locations of the ankle joint center of rotation for each
subject. The distance between the medial malleoli was then used to establish the foot
placement for the subjects perform the sitting paradigm.

In the sitting tasks, subjects were asked to sit on a raised stool at a height such that
their knee and hip angle were both in 90 degrees of flexion when the feet were placed on a
wooden platform. The wooden platform was attached to the stool over a single force plate
such that the only contacts with the force plate was the four legs of the raised stool.

In preparation for the reaching task, an arc with two round target microswitches
(diameter 4 cm) was placed in front of each subject. The first target mid-sagittal target
(MT) was placed at eye level in line with the mid-sagittal plane of the body. A 30 cm
distance from the outstretched arm was established for the MT and a second contralateral
target (CT) was located at 60-degrees from midline. All subjects reached with their
dominant arm (Table 1). In the standing task, the reach was initiated from a position
duplicating the carrying angle of the elbow (20 degrees of shoulder flexion and abduction,
30 degrees of elbow flexion). In the sitting task, the reach was initiated from the finger
switch (FS), which was placed beside the knee with the shoulder at 20 degrees of
abduction. FS, a force sensing resistor, generated a voltage output when depressed. A 5V
DC offset was generated when the FS or MT and CT were depressed at target acquisition.

The initiation of focal movements was executed under two behavioral conditions:
(1) externally-triggered (EX) and (2) self-initiated (SI). Subjects were instructed to focus
on a yellow light before any other stimulating cue. For EX trials subjects performed the
focal movement in response to the red light. Each collection period was 3000 ms starting at
the onset of the light (red LED). Five to seven trials were collected for each of the eight
tasks described above. The start time of each trial was controlled by the experimenter but
was separated by a random delay period unknown to the subjects. Repeated reaches to the
respective targets were performed sequentially. Subjects were instructed with the same
verbal commands. For example, “MT is the target of interest in this task, when you see the
onset of the red light, you will reach and depress the target as fast as you can. Be
sure not to lean forward prior to the light.” “For CT reaches, you are allowed to look at the target by turning your eyes or your neck slightly, but be sure not to lean side-ways and not to turn your trunk or your hip”. For SI movements, the subjects performed the first focal movement by reacting to the red light followed by several reaches at their own initiation until the end of an 18 sec collection period. Two or three blocks of 18-sec SI reaches were collected for both slow and fast velocities. All subjects are instructed with the identical command, “You will only be cued to reach by the illumination of the red light for the first trial; after that, you will reach at fast or slow speeds at your own time. Within a collection period of 18 seconds, you may reach several times. Please allow sufficient time to reposition yourself to the original body position before every reach. For CT reaches, you are allowed to look at the target by turning your eyes or your neck slightly, but be sure not to lean side-ways and not to turn your trunk or your hips.” Subjects were then asked to reiterate the task to confirm that they understood the task they were about to execute. For the testing of normal, young, healthy subjects, the number of reaches executed within each 18 second period ranged from four to six reaches for slow speed reaching and from five to seven reaches for fast speed reaching. Following contact with the target (MT or CT), subjects were instructed to return to the FS, depress it, and to foveate again on the yellow light before the next reach. The same experimental procedures and instructions were conducted in both the standing and sitting tasks. In order to minimize bias towards the experimental condition, three subjects were “blocked” to start with the standing tasks and the other three started with the sitting tasks. A resting period of at least 5-10 minutes was allowed after each task (speeds, targets, and body positions) to avoid fatigue.

Table 2: Experimental Conditions, Tasks, and Duration of Collection Period.

| Target                | Standing | Mid-sagittal (MT) | Contra\(|CT) | Sitting | Mid-sagittal (MT) | Contra\(|CT) |
|-----------------------|----------|-------------------|------------|---------|-------------------|------------|
| Condition \ Speeds    | Fast     | Slow              | Fast       | Slow    | Fast              | Slow       |
| Externally-Triggered  | 3000 | 3000              | 3000       | 3000    | 3000              | 3000       |
| Self-Initiated        | 18000    | 18000             | 18000      | 18000   | 18000             | 18000      |

All tasks for externally-triggered condition were repetitively tested for 5-10 trials
All tasks for self-initiated condition were repetitively tested 2-3 times for 5-10 trials
3.3 Data Collection / Recording System

3.3.1 Kinematics:

Body kinematics were monitored by a SELSPOT II system light emitting diodes (LEDs), pulsed at 1000 Hz, were placed at three predetermined locations on the side of the body ipsilateral to the reaching arm: half way in between the eye crease and the ear, the acromion process, and the distal ulnar styloid. A two camera system was used. In order to provide the three dimensional position of each of the three markers (anterior / posterior = x; superior / inferior = z; medial / lateral = z) an algorithm was used to calculate LED position offline.

3.3.2 Surface Electromyography (EMG):

The skin overlying the muscles to be tested was cleaned with alcohol to reduce skin impedance to less than 10 kΩ prior to recording. Medi-trace (Graphics Controls Canada Limited, 215 Hebert, Gananoque, Ontario, Canada, K7G 2Y2) silver-silver chloride surface recording pellet electrodes (diameter = 1cm) were placed 2 cm apart over the following muscle bellies along the length of the muscle fibers over the motor point: anterior deltoid (DELT) ipsilateral to the reaching arm, bilateral paraspinals (erector spinae) at the L3-L4 level (PS), rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), medial gastrocnemius (med-G), and soleus (S) muscles along the length of the muscle fibers.

EMG data was amplified using the Butterworth Neuroscan Model 5083 Syn-Amps amplifier (Neuroscan Inc., 1035 Sterling Road, Suite 103, Herdon, Virginia, USA, 22070-3806) with an input impedance of 10 MΩ, CMRR of 100 dB, signal to noise ratio and a gain of 20 000. EMG output was acquired using the SCAN program (Neurosoft Inc., 1035 Sterling Road, Suite 103, Herdon, Virginia, USA, 22070-3806) Data was stored on a Pentium 133, 32 bit computer (Dell, OptiPlex XMT 5133) for post-processing.

EMG data was collected at a sampling frequency of 1000 Hz and filtered digitally at 10-200 Hz (Butterworth, 12 dB/Octave). Data were collected and stored in an “epoch” mode for the EX condition. Multiple trials were stored in “continuous” mode in the SI condition. Both the epoch and continuous EMG files were full wave rectified and passed through a first order filter (linear envelope) of 50 Hz.
3.3.3 Kinetics/Ground Reaction Forces:

Two force plates (AMTI type OR6-3A, Advanced Mechanical Technology, Inc., Newton, MA, USA) were used to acquire data to estimate the COP location. Ground reaction forces were measured in three orthogonal directions (anterior-posterior/x, medial-lateral/y, vertical/z). Moments (Mx, My, Mz) about the x, y, and z-axis were also collected. Each force plate measures the forces and torques by a series of strain gauges arranged in a four-arm measuring bridge. The signal passes through six low noise cables to calibrated charge amplifiers. The sensitivity of the force plate was kept constant throughout the experiment. Baseline DC offsets were subtracted from acquired data. Signals were transmitted using an AD board that was controlled by a customized interface written using Labview data acquisition software (version 3.0, National Instruments). This data acquisition software also acted as a central control of the three data collection systems (Neuroscan for EMG, PDPl for kinematics, and AMTI force plates for kinetics). Sampling duration and sampling frequency were manually modified within this software to collect forces at 100 Hz.

3.4 Data Analysis

Raw kinematic data were run through a customized algorithm to compute the total displacement in three-dimensional space. This displacement data was further transformed to velocity profile by taking the first order derivative (Figure 3-3). The focal movement performance was quantified by measuring the peak wrist velocity (Figure 3-3: a), duration of the acceleration phase (time to peak velocity) (Figure 3-3: b) and the duration of the deceleration phase (time to target acquisition) (Figure 3-3: c). The difference in the onset time between wrist and the shoulder was also measured to examine the coupling between wrist and shoulder during a reaching movement (Figure 3-3: d).
Figure 3-3: Measurements and Data Quantification of Wrist Kinematic, EMG, and COP Excursion
A customized algorithm was used to compute measurements from conditioned EMG data. These measurements included: mean resting activity (500 ms prior to onset of muscle activity), onset latency (± 2 standard deviations from baseline) (Figure 3-3: e), and onset magnitude integrated for 100 ms after the onset of each muscle (Figure 3-3: f). Pilot data analysis revealed major differences between the EX and SI conditions in the activation pattern of the distal musculature of the lower extremity. Therefore, a detailed comparison of muscle onset time, and onset magnitude between behavioral conditions EX and SI was performed for bilateral tibialis anterior (TA) and medial gastrocnemius (med-G).

For the kinetic data, anterior-posterior forces (Fx), medial-lateral forces (Fy), vertical forces (Fz) and the moments around these three orthogonal axes from two force plates were used to calculate the COP. Both anterior-posterior COP and medial-lateral COP were expressed relative to the zero point of the force plates and were presented in time domain for analysis. During a rapid reaching movement, COP was characterized into two components; component I backwards and to the right; component II forward and to the left for a right-handed reach (Figure 3-3). Characteristics of COP in both anterior-posterior (AP) and medial-lateral (ML) direction were quantified temporally and spatially. Onset latency was determined by determining excursion of COP beyond a 4 mm band (Figure 3-3: g) (McIlroy and Maki, 1996) and component I time of peak amplitude and component II time of peak amplitude latency were recorded. In addition, peak component I displacement (peak I position – resting position) and peak component II displacement (peak II position – resting position) were also quantified in both AP and ML directions (Figure 3-3: h and i respectively).

Descriptive statistics were used to show the characteristics of the subjects. Individual means and global means, standard deviations (S.D.), standard errors of the means (S.E.M.) were calculated for all kinematic, EMG and kinetic measurements. Non-paired Student t-tests were calculated to compare the within subject difference between SI and EX conditions. A p value of 0.05 was used to determine statistical significance. When a significance level was detected a score of 1 was assigned. Frequency distributions of significant differences for each task were tabulated for the six subjects tested. In most cases, data are presented as both individual and global means.
Three-way analyses of variance (ANOVA), specifically Tukey's test, were used for comparison among the behavioural conditions, target locations, and speeds. When there was no statistically significance difference reported for main effect (EX vs. SI) but the interaction between behavioural conditions and speeds was statistically significant, then two-way ANOVA was then used for comparison of behavioural conditions and target locations for fast and slow speed reaches seperately. When the interaction was not statistically significant, the variance attributable to the interaction was included in the error variance, and the difference between behavioural conditions were tested without respect to the speeds. Two-way analyses of variance (ANOVA) were also used to compare the difference between initial postural positions (standing vs. sitting). Statistical significance was defined as \( p < 0.05 \) and will be shown as (*) in all tables and figures.
4 Results

4.1 Characteristics of Mid-sagittal Target Reach

Figure 4-1 shows representative EMG data during fast mid-sagittal reach at a fast speed while standing (MTf) from subject #4. Average target distance was 30 cm away from the extended reaching right arm. During reaching movements, proximal and distal muscle activities (EMG) and wrist velocities were measured. Center of pressure (COP) in both anterior-posterior (AP) and medial-lateral (ML) directions were also calculated from ground reaction forces collected from two force platforms. All measurements (EMG, kinematic, and COP) are temporally aligned to the activation of anterior deltoid (DELT) (prime mover) such that 0 ms is equivalent to the onset of DELT activation.

Figure 4-1, shows averaged EMG activity lined up to the onset of anterior deltoid displayed with one standard deviation (black area above). A biphasic-bursting pattern was evident for the DELT. Discrete anticipatory bursts of anterior lower extremity muscles (TA and RF) were activated bilaterally in a distal to proximal sequence followed by posterior muscle activation (RF and BF) (Figure 4-1b). Although bilateral TA were activated at approximately the same time, the magnitude of the ipsilateral TA was consistently greater. EMG activity associated with the focal movement was also characterized by alternating bursting of the agonist and antagonist muscles for fast pace reaches. TA, med-G, and RF, BF of the same side acted as agonist-antagonist pairs featuring reciprocal activation.

Comparison of muscle activity in MTf between EX (black) and SI (red) have shown that ipsilateral TA and BF onset magnitudes were markedly decreased despite the fact that the initial deltoid activity being similar. Bilateral med-G have shown an earlier onset time with similar onset magnitude. Bilateral TA and med-G are the most indicative muscle groups to demonstrate the difference in activation pattern for the EX and SI conditions, their activities were used as main measurement of postural adjustment during reaches in later parts of the analysis.
Figure 4-1a: A representative example of the characteristics of EMGs excursions during MTf reaches
Figure 4-1b: A representative example of pattern of postural EMGs during mid-sagittal reach at fast speed.

Characteristics of COP excursion presented in a stabilogram were broken down into two major components (Figure 4-2). The onset of the component I (backward and right excursion) occurred approximately 280 ms prior to deltoid onset reversing polarity at about the time of DELT onset. Component II (forward and left excursion) reached peak and reversed polarity at about target acquisition 400 ms after DELT onset. The component I of the COP excursion appeared to shift pressure posterior to the COM so as to shift the body mass forward. Such movement of COM has been reported necessary for forward body lean and for target acquisition. The second component was characterized by the quick reversal of polarity of COP. The function of which was also to shift pressure in front of the COM so as to stop the continuing forward shifting of COM when the target is acquired.
Figure 4-2: A representative example of the characteristics of COP excursion during a mid-sagittal target reach at fast
4.2 Motor Performance

The velocity profile is a bell shape curve slightly skewed to the left as previously reported with a prolonged deceleration phase toward the target acquisition (Soechting and Lacquaniti, 1981; Hollerbach and Flash, 1982; Smith, 1993; Dick 1995). In order for the effect of the task conditions on the balance control of reaching movements to be evaluated, the performance of the focal movement must be similar for both the EX and SI conditions. Mean peak wrist velocities and their standard error for the eight task conditions tested are shown in Figure 4-3. No significant difference between the EX and SI conditions for both standing and sitting tasks is seen (Figure 4-3). Differences were evident only when comparing reaches to different target location. For example, peak wrist velocity for the EX contralateral target at fast speed (CTf) (3.90 ± 0.37 m/second) is significantly faster than EX mid-sagittal target reach at a fast speed (MTf) (3.17 ± 0.25 m/second) (Figure 4-3). Analysis of “time to peak” (acceleration phase) and “peak to target acquisition” (deceleration phase) duration have shown that the EX and SI conditions are not significantly different (Figure 4-4, 4-5).

Although focal movement performance as measured by wrist velocity was similar for the EX and SI conditions, the initial postural position between EX and SI could be different. Thus the coordination or coupling between onset of the focal movement and the onset of the trunk movement was examined. Differences between onset time of wrist movement and the trunk movement were calculated to examine whether the trunk moved earlier in any of the two conditions (difference = wrist onset time – shoulder onset time). A negative value in this calculation would imply that the wrist movement occurred before the shoulder movement. A positive value would imply that the shoulder moves earlier than the trunk. Results have shown that except for fast speed reaches in the sitting position there was no difference in the wrist-shoulder coupling between EX and SI for all other tasks (Figure 4-6). That is, the initial trunk positions relative to the wrist of the reaching arm was similar for the EX and SI conditions in all standing reaching tasks (MTf, MTs, CTf, CTs). However, such relationship needs further investigations in the sitting reaching tasks.

Although the shoulder-wrist coupling did not reach statistical significance in all standing tasks, there was a trend that the SI condition could potentially involve with earlier trunk movement than the EX condition.
Figure 4-3: Peak wrist velocities for all tasks (mid-sagittal target, contralateral target, fast and slow) and conditions (EX and SI)
Figure 4-4: Time of the acceleration phase (time between movement onset to peak wrist velocity)

Figure 4-5: Time of the deceleration phase (time between peak wrist velocity to target acquisition)
Figure 4-6: Coupling of wrist and shoulder movement during reaches: difference in onset time of movement
4.3 Stand-Reach: EMG and COP analysis

Since the muscle activation pattern and the base of support during reaching are fundamentally different for standing and sitting body positions, the following detailed analysis of the characteristics of EMG and COP profiles are separated. Measurements of postural muscle activity during reaches to the MT and CT in standing are reported followed by the sitting position in this section.

4.3.1 EMG analysis

Inter-subject variability for EMG is well recognized and is very dependent on experimental setup. Therefore, for the purpose of these experiments intra-subject analysis of EMG was used. In other words, trial by trial EMG analysis was carried out for individual subjects. Those individuals who had significantly different results for a given task (p<0.05) was tallied and presented in a summary table. However, in order to interpret the main effect of task on muscle activity, “group averages” was also calculated and presented.

Preliminary analysis of the EMG profiles have demonstrated that the major difference between EX and SI for Stand-Reach tasks was in the distal lower extremity musculature; consequently, the latency and onset magnitude for TAs and med-Gs were the two muscle groups selected for detailed analysis.

For mid-sagittal target reaches at fast speed (MTf), the difference between the EX and SI conditions was clearly demonstrated by TA and med-G activity. Both TA and med-G were consistently activated earlier in the SI condition as compared to the EX condition in MTf (Figure 4-7). All 6 subjects had earlier TAi onset latency and the majority of subjects had earlier TAc onset latencies (4 out of 6) (Table 3). Furthermore, analysis of med-Gi and med-Gc also demonstrated that the onset latency for the SI condition was earlier than for the EX condition (Table 3). Differences between the EX and SI conditions were also evident in the 100 ms onset magnitude. Consistently, all 6 subjects had smaller TAi and TAc onset magnitude and 4 out 6 had smaller med-Gi and med-Gc onset magnitude in MTf. In summary, EMG data for the MTf reach demonstrated that distal musculature was activated earlier in the SI condition but with lower magnitude as compared to the EX
condition. A total of four sub tasks derived from two speeds and two target locations were tested in the standing position. (Appendix III)

Contralateral reaches at fast speed (CTf) and at slow speed (CTs) also demonstrated earlier TAI activation and smaller TAI and TAC onset magnitude in 5 out of 6 subjects. However, TAC, med-Gi and med-Gc showed a less clear systematic difference. Comparison for reaches at the slow speeds were not clear as EMG magnitude was often minimal and variable (Table 3) (Appendix II).

Overall tally of the EMG data indicates that SI is distinguishable from EX with the following characteristics in the standing paradigm: earlier onset time for TAI (SI: EX = 13:5), med-Gi (SI: EX = 9:1), med-Gc (SI: EX = 10:1) and the smaller onset magnitude of TAI (SI: EX = 19:0) and TAC (SI: EX = 18:3).

### Table 3: Summary of Lower Extremity EMG for Stand-Reach Tasks

<table>
<thead>
<tr>
<th>Tasks</th>
<th>MTf</th>
<th>MTs</th>
<th>CTf</th>
<th>CTs</th>
<th>SUM</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earlier TAI for SI</td>
<td>6*</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>4*</td>
<td>1</td>
</tr>
<tr>
<td>Earlier TAC for SI</td>
<td>4*</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2*</td>
<td>2</td>
</tr>
<tr>
<td>Smaller TAI magnitude for SI</td>
<td>6*</td>
<td>0</td>
<td>5*</td>
<td>0</td>
<td>5*</td>
<td>0</td>
</tr>
<tr>
<td>Smaller TAC magnitude for SI</td>
<td>6*</td>
<td>0</td>
<td>5*</td>
<td>1</td>
<td>5*</td>
<td>0</td>
</tr>
<tr>
<td>Earlier med-Gi for SI</td>
<td>4*</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Earlier med-Gc for SI</td>
<td>4*</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Smaller med-Gi magnitude for SI</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Smaller med-Gc magnitude for SI</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

* where majority of subjects have difference (n > 3)  
indifference results are not counted for  
MTf/MTs: mid-sagittal target reach at fast/slow speed while standing  
CTf/CTs: contralateral reach at fast/slow speed while standing  
TAI: ipsilateral tibialis anterior  
TAC: contralateral tibialis anterior  
med-Gi: ipsilateral medial Gastrocnemius  
med-Gc: contralateral medial Gastrocnemius
Figure 4.7: EX versus SI mid-sagittal target reach at fast speed: relative EMG onset time (to DELT) and the 100 ms EMG onset magnitude
4.3.2 COP Excursion – Relative Latency and Magnitude

4.3.2.1 Latency Characteristics of COP Excursion

As seen in Figure 4-8 earlier relative COP onset time, component I peak time, and component II peak time in the SI condition as compared to the EX condition was evident in the MTf reach. The group average AP COP onset time for the SI condition was at 140.9 ± 28.7 ms and for the EX condition was at 30.3 ± 68.7 ms prior to deltoid onset. Although the group average for the onset time of ML COP in the SI condition was not significantly earlier than in the EX condition, its value was still slightly earlier in the SI condition (-91.7 ± 39.5 ms) than that the EX condition (-60.2 ± 59.3 ms) (Figure 4-8, Table 5). This supports the observation from the EMG analysis that the distal musculature (TA and med-G) is activated earlier in the SI condition. To summarize the result, for MTf, 5 out of 6 subjects had significant earlier onset of AP COP excursion and earlier peak for component I and component II in the SI condition (3 out of 6) (Table 4).

Similar to the MT reach, the CT reach at fast speeds while standing (CTf) also showed earlier COP onset times, component I peak time and component II peak time for the SI condition as compared to the EX condition in both AP and ML directions (Table 3, Appendix (III)). The overall average of the means and S.E.M. showed that the onset time of the AP COP excursion occurred at 207 ± 46.9 and 120.8 ± 109.6 ms prior to deltoid initiation for the EX and SI conditions respectively. The overall average of the means for ML COP also showed that COP onset occurs at 191.4 ± 25.8 ms and 125.9 ± 44.2 ms prior to deltoid for the EX and SI conditions respectively (p<0.05).

Similar to the EMG data, COP excursion in both the AP and ML directions for reaches at slow speeds were more highly variable between subjects. MTs and showed higher inter-subject variability with no systematic difference (Table 4, 5, 6).
Table 4: Comparison of the Latency of EX and SI COP Excursion for Stand-Reach Tasks

<table>
<thead>
<tr>
<th>Tasks</th>
<th>MTY</th>
<th>MTS</th>
<th>CTY</th>
<th>CTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
<td>EX</td>
</tr>
<tr>
<td>AP COP</td>
<td>Earlier COP onset</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Early COP peak #1</td>
<td>3</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Early COP peak #2</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>ML COP</td>
<td>Earlier COP onset</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Early COP peak #1</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Early COP peak #2</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

(1 count reveals a statistically significant difference between EX and SI conditions for 1 subject)

SI: SI Reach
EX: EX Reach
AP COP: COP excursion in the anterior-posterior direction
ML COP: COP excursion in the medial-lateral direction

Table 5: AP COP Onset Time for Stand-Reach Tasks

<table>
<thead>
<tr>
<th>AP COP</th>
<th>MTY</th>
<th>MTS</th>
<th>CTY</th>
<th>CTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EX</td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
</tr>
<tr>
<td>Pooled</td>
<td>-30.3* (68.7)</td>
<td>-149.9 (29.7)</td>
<td>-49.0 (91.9)</td>
<td>-80.0 (143.4)</td>
</tr>
<tr>
<td>n6</td>
<td>-27.2 (34.1)</td>
<td>-80.4 (77.5)</td>
<td>-68.0 (87.6)</td>
<td>-66.0 (165.4)</td>
</tr>
<tr>
<td>n5</td>
<td>-46.8* (74.0)</td>
<td>-123.3 (108.9)</td>
<td>112.0 (218.6)</td>
<td>-40.0 (172.5)</td>
</tr>
<tr>
<td>n4</td>
<td>-277.4* (36.3)</td>
<td>-163.1 (111.1)</td>
<td>-390.3 (400.7)</td>
<td>4.7 (190.5)</td>
</tr>
<tr>
<td>n3</td>
<td>-44.4* (71.6)</td>
<td>-206.2 (144.2)</td>
<td>-164.7 (229.2)</td>
<td>-331.4 (221.7)</td>
</tr>
<tr>
<td>n2</td>
<td>-110.0* (59.9)</td>
<td>-225.8 (84.9)</td>
<td>184.8 (412.3)</td>
<td>-158.0 (103.3)</td>
</tr>
<tr>
<td>n1</td>
<td>230.2* (117.0)</td>
<td>-46.8 (144.8)</td>
<td>-67.7 (80.0)</td>
<td>-21.0 (225.5)</td>
</tr>
</tbody>
</table>

Table 6: ML COP Onset Time for Stand-Reach Tasks

<table>
<thead>
<tr>
<th>ML COP</th>
<th>MTY</th>
<th>MTS</th>
<th>CTY</th>
<th>CTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EX</td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
</tr>
<tr>
<td>Pooled</td>
<td>-60.1 (59.3)</td>
<td>-91.7 (39.9)</td>
<td>-148.2 (84.9)</td>
<td>-21.0 (126.3)</td>
</tr>
<tr>
<td>n6</td>
<td>-17.5 (79.5)</td>
<td>-95.0 (101.2)</td>
<td>-94.0* (97.9)</td>
<td>277.3 (186.0)</td>
</tr>
<tr>
<td>n5</td>
<td>16.8 (72.6)</td>
<td>-25.8 (38.2)</td>
<td>172.0 (219.1)</td>
<td>3.3 (94.0)</td>
</tr>
<tr>
<td>n4</td>
<td>-287.4 (26.5)</td>
<td>-159.4 (80.5)</td>
<td>-397.8 (409.5)</td>
<td>-128.7 (171.5)</td>
</tr>
<tr>
<td>n3</td>
<td>-88.7 (78.6)</td>
<td>-160.2 (162.9)</td>
<td>-358.0 (256.9)</td>
<td>-500.0 (14.1)</td>
</tr>
<tr>
<td>n2</td>
<td>-126.7 (60.2)</td>
<td>-178.3 (110.8)</td>
<td>-124.0 (108.7)</td>
<td>-32.0 (207.5)</td>
</tr>
<tr>
<td>n1</td>
<td>142.2 (58.4)</td>
<td>68.2 (154.5)</td>
<td>47.7* (76.2)</td>
<td>366.5 (108.0)</td>
</tr>
</tbody>
</table>

* Pooled: average of means (1 standard error of the mean)
* Comparison between EX and SI using Student t-test, p < 0.05
* Individual: mean (1 standard deviation)
SI: SI Reach
EX: EX Reach
n 6 to 1: subject 6 to 1
Anterior-Posterior Direction

Medial-Lateral Direction

Legend:
0 msecond = deltoid onset time
- - Externally-Triggered Reach
- - Self-Initiated Reach

Figure 4-8: EX versus SI mid-sagittal target reach at fast speed: relative latency of COP excursion
4.3.2.2 Amplitude Characteristics of COP Excursion

During reaches to both the MT and the CT, a larger backward and forward COP excursion in EX as compared to SI was evident in the AP direction (Figure 4-9). For MTf task, the peak forward displacement were -0.082 ± 0.016m and -0.043 ± 0.011m for the EX and SI conditions respectively and the peak backward displacement were 0.199 ± 0.033m and 0.096 ± 0.021m for the EX and SI conditions respectively (Table 7). However, comparison between EX and SI for ML COP excursion in MTf has demonstrated that effect of condition on COP displacement is different in the two components. Similar to the AP direction, component I peak ML COP displacement in the EX condition was larger than the SI condition. But unlike the AP direction, component II peak ML COP displacement in the SI condition was in fact larger than the EX condition (Figure 4-9).

Table 7: Peaks of COP Excursion for Stand-Reach Tasks

<table>
<thead>
<tr>
<th>TASKS</th>
<th>EX (m)</th>
<th>SI (m)</th>
<th>EX (m)</th>
<th>SI (m)</th>
<th>EX (m)</th>
<th>SI (m)</th>
<th>EX (m)</th>
<th>SI (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP COP (I)</td>
<td>-0.082* (0.016)</td>
<td>-0.063 (0.011)</td>
<td>-0.024* (0.011)</td>
<td>-0.012 (0.004)</td>
<td>-0.180* (0.025)</td>
<td>-0.110 (0.018)</td>
<td>-0.095* (0.012)</td>
<td>-0.049 (0.014)</td>
</tr>
<tr>
<td>AP COP (II)</td>
<td>0.117* (0.022)</td>
<td>0.054 (0.014)</td>
<td>0.116* (0.017)</td>
<td>0.054 (0.016)</td>
<td>0.233 (0.031)</td>
<td>0.230 (0.037)</td>
<td>0.280* (0.005)</td>
<td>0.231 (0.016)</td>
</tr>
<tr>
<td>ML COP (I)</td>
<td>-0.065* (0.014)</td>
<td>-0.028 (0.027)</td>
<td>-0.023* (0.005)</td>
<td>-0.011 (0.022)</td>
<td>-0.154 (0.024)</td>
<td>-0.127 (0.022)</td>
<td>-0.067 (0.009)</td>
<td>-0.055 (0.016)</td>
</tr>
<tr>
<td>ML COP (II)</td>
<td>0.053* (0.015)</td>
<td>0.148 (0.017)</td>
<td>0.045* (0.013)</td>
<td>0.133 (0.019)</td>
<td>0.203 (0.037)</td>
<td>0.270 (0.032)</td>
<td>0.227* (0.012)</td>
<td>0.292 (0.010)</td>
</tr>
</tbody>
</table>

Mean (± standard error) (unit = m)
* p<0.05 for comparison between EX and SI
COP (I): component I peak COP excursion
COP (II): component II peak COP excursion

Three-way ANOVA for the comparison among behavioural conditions, target locations and speeds of reaches and their interactions was performed. The peak COP (I) and COP (II) displacements were significantly different for the EX and SI conditions. Specifically, smaller AP COP (I) and AP COP (II) along with larger ML COP (II) were found to be associated with the SI condition for all target locations and reaching speeds (Table 8). Although the ML COP (I) did not reach significance using a three-way ANOVA, two-way ANOVA for comparison between behavioural conditions and target locations for fast speed reaches only demonstrated significant differences between the EX and SI condition (Table 9). Specifically, larger ML COP (I) is associated with fast reaches in the SI condition.
Table 8: P value of three-way ANOVA for the Comparison between Conditions, Target Locations, and Speeds in the Standing Position

<table>
<thead>
<tr>
<th>Condition</th>
<th>Target</th>
<th>Speed</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SI vs. EX</td>
<td>MT vs. CT</td>
<td>Fast vs. Slow</td>
</tr>
<tr>
<td>Wrist Velocity</td>
<td>0.663</td>
<td>0.001*</td>
<td>0.001*</td>
</tr>
<tr>
<td>TA Onset Time</td>
<td>0.85**</td>
<td>0.437</td>
<td>0.015*</td>
</tr>
<tr>
<td>TA Onset Magnitude</td>
<td>0.001*</td>
<td>0.857</td>
<td>0.001*</td>
</tr>
<tr>
<td>AP COP Onset Time</td>
<td>0.17**</td>
<td>0.024*</td>
<td>0.973</td>
</tr>
<tr>
<td>ML COP Onset Time</td>
<td>0.733</td>
<td>0.066</td>
<td>0.818</td>
</tr>
<tr>
<td>AP COP (I)</td>
<td>0.001*</td>
<td>0.001*</td>
<td>0.001*</td>
</tr>
<tr>
<td>ML-COP (I)</td>
<td>0.009**</td>
<td>0.001*</td>
<td>0.001*</td>
</tr>
<tr>
<td>AP COP (II)</td>
<td>0.001*</td>
<td>0.001*</td>
<td>0.38</td>
</tr>
<tr>
<td>ML COP (II)</td>
<td>0.001*</td>
<td>0.001*</td>
<td>0.754</td>
</tr>
</tbody>
</table>

*, statistically significant at P < 0.05
**, statistically significant at P < 0.05 only at fast speed reaches (see Table 9).

Table 9: P value of two-way ANOVA for the Comparison between Conditions, Target Locations for Fast Speed Reaches in the Standing Position, a Supplementary Comparison for Non-Significance in Table 8

<table>
<thead>
<tr>
<th>Condition</th>
<th>Target</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SI vs. EX</td>
<td>MT vs. CT</td>
</tr>
<tr>
<td>TA Onset Time</td>
<td>0.904</td>
<td>0.867</td>
</tr>
<tr>
<td>AP COP Onset Time</td>
<td>0.907</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ML COP Onset Time</td>
<td>0.433</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ML COP (I)</td>
<td>0.007</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Table 10, a tabulated summary of the comparison of the two amplitudes of COP excursion in AP and ML directions, demonstrates that for both MT reach and CT reach, more subjects have larger overall AP COP excursion (backward and forward) for EX as compared to SI (for MT; EX : SI = 14 : 0, for CT; EX : SI = 20 : 0). More subjects had a larger component I ML COP amplitude for the EX condition (for MT; EX : SI = 3:2, for CT; EX : SI = 8 : 1) but more subjects had larger component II ML COP amplitude for the SI condition (for MT; EX: SI=0:12, for CT; EX: SI = 1:11).
Table 10: Comparison of COP amplitude between EX and SI Stand-Reach Tasks

<table>
<thead>
<tr>
<th></th>
<th>MTY</th>
<th>MTs</th>
<th>CTF</th>
<th>CTS</th>
<th>MT SUM</th>
<th>CT SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EX</td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
</tr>
<tr>
<td>AP COP</td>
<td>Larger COP (I)</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Larger COP (II)</td>
<td>4</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>ML COP</td>
<td>Larger COP (I)</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Larger COP (II)</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Larger COP (I) &amp; COP (II)</td>
<td>6</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Larger COP (I) &amp; COP (II)</td>
<td>2</td>
<td>9</td>
<td>1</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

1 count = 1 subject with a significant difference between EX and SI conditions, max = 6
AP COP: COP excursion in the anterior-posterior direction
ML COP: COP excursion in the medial-lateral direction
COP (I): component I peak COP excursion
COP (II): component II peak COP excursion
Figure 4-8: EX versus SI mid-sagittal target reach at fast speed - segmental amplitude of AP COP and ML COP excursion
When analyzing COP excursion in the spatial domain with AP COP plotted against ML COP, the difference between the EX and SI conditions was even more evident. Figure 4-10 is a plot of average peak AP COP displacements against peak ML COP displacements across the various tasks with varying speeds for the target locations. Each individual point represents the average value for four to seven trials in one subject. The lower right quadrant represents the component I of COP excursion in the direction away from the target (backward and rightward). The upper left quadrant represents the component II of COP excursion towards the target (forward and leftward). Several distinct features can be observed from the plot: (1) There is strong correlation of peak AP COP and ML COP displacement across tasks that varies within target location and speed of reach for both the EX and SI conditions ($r$ for EX = 0.98, $r$ for SI = 0.96). In summary, high correlation between the distance of displacement in AP and ML direction across tasks was evident. This observation is true for both the EX and SI conditions; (2) The slope of the regression line across tasks under the EX condition is higher than the slope of the regression line across tasks under the SI condition (slope for EX = -1.204, slope for SI = -0.756). (3) Both lines almost intercept with the mid point (0,0) and have no apparent values that lie within the upper right and lower left quadrants in both the EX and SI conditions. (4) The amplitude of the initial peak COP displacement (component I) away from the target is smaller than the amplitude of the end peak COP displacement (component II).
Regression Line:
- Externally-Triggered
  slope = -1.204, r = 0.98
- Self-Initiated
  slope = -0.756, r = 0.96

Figure 4-10: Comparison between The EX and SI conditions for averaged peak COP displacement during Stand-Reach tasks, a regression interpretation.
There is a trend that SI COP excursion shifts more towards the ML direction (open symbols are more toward the left side of the graph) across all Stand-Reach tasks as seen in Figure 4-11, a plot of the grouped peak AP COP displacement (component I and component II) versus grouped peak ML COP displacement. This plot is similar to Figure 4-10 with the exception that the mean ± S.E.M. for all six subjects are presented with their standard error of the mean. The COP displacement in both AP and ML direction are larger for CT reaches as compared to MT reaches (blue versus black) in both COP (I) and COP (II). It is clear that the more challenging tasks tend to have larger displacements and the easier tasks tend to have smaller displacement. The more challenging tasks being those that require reaches at fast speeds and towards contralateral space. In addition, relationship between speed of reach and COP is also demonstrated. Reaching at fast speeds is associated with larger peak COP displacement and reaching at slow speed is associated with smaller peak COP displacement (blue versus purple and black versus red). Furthermore, the relationship between the AP COP excursion and ML COP excursion during Stand-Reach tasks displays a specific directionality. During reaching with the right arm, backward COP excursion is always associated with rightward excursion and forward COP excursion is associated with the leftward excursion.
Figure 4-11: Averaged peak AP COP versus ML COP displacement during component (I) and component (II) COP excursion for Stand-Reach tasks, mid-sagittal target and contralateral target at fast and slow speeds.
4.4 Sit-Reach: EMG and COP Analysis

4.4.1 A Representative Example of Characteristics of mid-sagittal Target Reaches:

In contrast to the Stand-Reach tasks, the Sit-Reach tasks have overall lower levels of distal lower limb muscle activity during reaches at similar speeds as seen in a representative example of MT reach (Figure 4-12, Appendix (II)). However, focal movement DELT EMG characteristics remained similar in both magnitude and the onset latency. The similarity of the prime mover activity and the decreased lower extremity muscle activity confirms that the muscle recruitment pattern for the Sit-Reach tasks is different from the Stand-Reach tasks. As expected, the activation the agonist-antagonist muscles are not as apparent in the non-weight-bearing lower extremity for the Sit-Reach tasks (Figure 4-12).

Comparison of the muscle activity pattern between the EX (black) and SI (red) conditions showed no consistent differences.

4.4.2 EMG analysis:

Lack of muscle activity in the lower extremities and the trunk (not shown in the plots) in the stable sitting position made comparison between EX and SI problematic. There is no clear distinction between conditions for the lower extremity EMG activity (TA and med-G). Both the onset latency and the onset magnitude vary in consistently indicating that EMG in the present study is not the best measurement for comparison between EX and SI was in the sitting position (Table 9). Perhaps, other muscles would reveal more indicative difference between conditions in the sitting position, i.e. the gluteus medius, the erector spinae or the rectus abdominus. Although the EMG analysis in the present study did not demonstrate a measurable differences between the EX and SI conditions, COP analysis in the later section demonstrates that EX condition was associated with larger AP excursion and the SI condition with larger ML excursion (Figure 4-14, Appendix (IV)).
Table 11: Summary of Lower Extremity EMG during Reaching while Sitting

<table>
<thead>
<tr>
<th>Tasks</th>
<th>SMTY</th>
<th>SMTs</th>
<th>SCTY</th>
<th>SCTs</th>
<th>SUM</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earlier TAI for SI</td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
<td>EX</td>
</tr>
<tr>
<td>Earlier TAc for SI</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Earlier TAI magnitude for SI</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Earlier med-GI for SI</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Earlier med-Gc for SI</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Earlier med-Gc magnitude for SI</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Smaller med-Gc magnitude for SI</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

SMTY: mid-sagittal target reach at fast/slow speed while sitting
SCTY: contralateral reach at fast/slow speed while sitting

4.4.3 COP Excursion – Relative Latency and Magnitude
4.4.3.1 Latency Characteristics of COP Excursion

Table 12, a summary chart for the comparison of COP excursion between SI reaches and EX reaches while sitting, shows that most of the difference in COP excursion between EX and SI is in the ML direction. The COP in the AP direction varies systematically between task conditions. Mid-sagittal target reaches at slow speeds (SMTs) and contralateral reach at fast and slow speeds (SCTf and SCTs) were different in ML COP excursion between the EX and SI conditions. For SMTs task, 4 out of 6 subjects had significantly earlier onset of ML COP excursion (SI: 326.9 ± 62.3 ms, EX: 36.9 ± 31.6 ms) (Table 12, Appendix (III)).

For the contralateral reach at a fast speed while sitting (SCTf), the majority of subjects had significantly earlier ML COP onset time in the SI condition (-29.9 ± 69.4 ms) as compared to EX condition (20.7 ± 39.7 ms) (Table 12, Figure 4-13). Earlier peak component I COP displacement for the SI condition was also observed although there was non-significant difference at the p<0.05.

For the contralateral reach at the slow speed while sitting (SCTs), the majority of the subjects also had significantly earlier ML COP onset in the SI condition (-48.2 ± 37.7 ms) as compared to the EX condition (119.1 ± 47.4 ms) (Table 12). However, the latencies of the peak COP displacements in both the forward and backward directions were not clearly different between the EX and SI conditions.
Table 12: Comparison of the latency of EX and SI COP Excursion for Sit-Reach Tasks

<table>
<thead>
<tr>
<th>Tasks</th>
<th>SMTY</th>
<th>SMTs</th>
<th>SCTY</th>
<th>SCTs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SI compared to EX</td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
</tr>
<tr>
<td>AP COP</td>
<td>Earlier COP onset</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Earlier COP peak #1</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Earlier COP peak #2</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>ML COP</td>
<td>Earlier COP onset</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Earlier COP peak #1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Earlier COP peak #2</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

(1 count reveals statistical difference between EX and SI conditions for 1 subject)

SI: SI Reach; EX: EX Reach
AP COP: COP excursion in the anterior-posterior direction
ML COP: COP excursion in the mediolateral direction
COP onset: the time of which where COP excursion exceed threshold
COP peak #1: peak of the component 1 COP excursion (backward / rightward)
COP peak #2: peak of the component 1 COP excursion (forward / leftward)

---

Table 13: AP COP Onset Time for Sit-Reach Tasks

<table>
<thead>
<tr>
<th>AP COP</th>
<th>SMTY</th>
<th>SMTs</th>
<th>SCTY</th>
<th>SCTs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EX</td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
</tr>
<tr>
<td>Pooled</td>
<td>58.4* (33.3)</td>
<td>-8.1 (39.3)</td>
<td>164.5* (76.0)</td>
<td>94.0 (27.5)</td>
</tr>
<tr>
<td>a6</td>
<td>89.0 (17.0)</td>
<td>-9.5 (146.3)</td>
<td>192.6 (124.8)</td>
<td>100.0 (101.8)</td>
</tr>
<tr>
<td>a5</td>
<td>-3.6 (25.6)</td>
<td>-24.3 (62.9)</td>
<td>142.3 (31.8)</td>
<td>48.0 (138.8)</td>
</tr>
<tr>
<td>a4</td>
<td>-18.8* (46.4)</td>
<td>-158.4 (42.6)</td>
<td>-96.5 (157.9)</td>
<td>20.4 (119.4)</td>
</tr>
<tr>
<td>a3</td>
<td>81.8 (12.5)</td>
<td>85.7 (38.1)</td>
<td>15.4* (64.3)</td>
<td>99.0 (105.5)</td>
</tr>
<tr>
<td>a2</td>
<td>103.5 (9.3)</td>
<td>65.5 (29.7)</td>
<td>372.3 (50.2)</td>
<td>218.0 (68.8)</td>
</tr>
<tr>
<td>a1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

---

Table 14: ML COP Onset Time for Sit-Reach Tasks

<table>
<thead>
<tr>
<th>ML COP</th>
<th>SMTY</th>
<th>SMTs</th>
<th>SCTY</th>
<th>SCTs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EX</td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
</tr>
<tr>
<td>Pooled</td>
<td>4.0 (32.7)</td>
<td>23.6 (48.7)</td>
<td>36.9* (31.6)</td>
<td>326.9 (62.3)</td>
</tr>
<tr>
<td>a6</td>
<td>45.0* (18.3)</td>
<td>-59.7 (76.6)</td>
<td>38.6* (22.6)</td>
<td>498.0 (63.1)</td>
</tr>
<tr>
<td>a5</td>
<td>-56.4 (74.6)</td>
<td>5.7 (56.3)</td>
<td>90.8 (7.0)</td>
<td>178.0 (243.7)</td>
</tr>
<tr>
<td>a4</td>
<td>-103.5 (35.9)</td>
<td>-138.4 (122.4)</td>
<td>8.2 (15.4)</td>
<td>163.0 (221.7)</td>
</tr>
<tr>
<td>a3</td>
<td>66.8* (10.7)</td>
<td>166.0 (91.1)</td>
<td>-42.6* (80.7)</td>
<td>239.0 (158.7)</td>
</tr>
<tr>
<td>a2</td>
<td>70.2* (9.8)</td>
<td>108.8 (38.2)</td>
<td>159.4* (41.4)</td>
<td>508.0 (167.2)</td>
</tr>
<tr>
<td>a1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Pooled: average of means (1 standard error of the mean)
Individual: mean (1 standard deviation)
* p<0.05 for comparison between EX and SI
NA: not available
SI: SI Reach
EX: EX Reach
n=1: subject 6 to 1
Figure 4-12: A representative example of the characteristics of mid-sagittal target reach while sitting (SMTf)
Figure 4-13: mid-sagittal target at fast speed (MTf): relative latency of COP excursion
4.4.3.2 Amplitude Characteristics of COP Excursion

Table 13, a tabulated summary of the comparison of the two amplitudes of COP excursion in AP and ML directions for Sit-Reach tasks, demonstrates that regardless of the reaching speeds, for MT, more subjects have a larger AP COP (I) and AP COP (II) excursion in the EX condition (EX: SI = 12:0) and more subjects have larger overall ML COP displacement for the SI condition (EX: SI = 0:14). For the contralateral target, only the ML COP had clear interpretation: larger ML COP (I) displacement in the EX condition and larger ML COP (II) displacement in the SI condition are seen in 4 out of 6 subjects (Table 15). In other words, EX reaches to MT tend to be associated with larger peak AP COP (II) and the SI reaches tend to be associated with larger ML COP (II) in the sitting position (Figure 4-14, Table 16) [Appendix (IV)]. A three-way ANOVA demonstrated that there was a significance difference in COP (II) displacements between the EX and SI conditions (Table 17).

Table 15: Comparison of COP amplitude between EX and SI Sit-Reach Tasks

<table>
<thead>
<tr>
<th></th>
<th>SMTF</th>
<th>SMTB</th>
<th>SCTY</th>
<th>SCTs</th>
<th>MT SUM</th>
<th>CT SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP COP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larger COP (I)</td>
<td>EX</td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Larger COP (II)</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>ML COP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larger COP (I)</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Larger COP (II)</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>AP COP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larger COP (I) and COP (I)</td>
<td>8</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Larger COP (I) and COP (II)</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>6</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 16: Peaks of COP Excursion for Sit-Reach Tasks

<table>
<thead>
<tr>
<th>TASKS</th>
<th>SMTF</th>
<th>SMTB</th>
<th>SCTY</th>
<th>SCTs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EX</td>
<td>SI</td>
<td>EX</td>
<td>SI</td>
</tr>
<tr>
<td>AP COP (I)</td>
<td>-0.02</td>
<td>(0.01)</td>
<td>-0.01</td>
<td>(0.001)</td>
</tr>
<tr>
<td>AP COP (II)</td>
<td>0.01</td>
<td>(0.002)</td>
<td>0.01</td>
<td>(0.003)</td>
</tr>
<tr>
<td>ML COP (I)</td>
<td>-0.01</td>
<td>(0.001)</td>
<td>-0.01</td>
<td>(0.001)</td>
</tr>
<tr>
<td>ML COP (II)</td>
<td>0.01</td>
<td>(0.001)</td>
<td>0.01</td>
<td>(0.001)</td>
</tr>
</tbody>
</table>

* P < 0.05 for comparison between EX and SI mean (± standard error) (unit = m)
COP (I): component I peak COP excursion
COP (II): component II peak COP excursion
Table 17: P value of three-way ANOVA for the comparison between conditions, target locations, and speed in the sitting position

<table>
<thead>
<tr>
<th>Condition</th>
<th>Target</th>
<th>Speed</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SI vs. EX</td>
<td>MT vs. CT</td>
<td>Fast vs. Slow</td>
</tr>
<tr>
<td>Wrist Velocity</td>
<td>0.342</td>
<td>0.001*</td>
<td>0.801*</td>
</tr>
<tr>
<td>TA Onset Time</td>
<td>0.975</td>
<td>0.078</td>
<td>0.002*</td>
</tr>
<tr>
<td>TA Onset Magnitude</td>
<td>0.454</td>
<td>0.130</td>
<td>0.115</td>
</tr>
<tr>
<td>AP COP Onset Time</td>
<td>0.707</td>
<td>0.155</td>
<td>0.022</td>
</tr>
<tr>
<td>ML COP Onset Time</td>
<td>0.520</td>
<td>0.024*</td>
<td>0.005*</td>
</tr>
<tr>
<td>AP COP (I)</td>
<td>0.196</td>
<td>0.029*</td>
<td>0.001</td>
</tr>
<tr>
<td>ML COP (I)</td>
<td>0.500</td>
<td>0.001*</td>
<td>0.001</td>
</tr>
<tr>
<td>AP COP (II)</td>
<td>0.001*</td>
<td>0.315</td>
<td>0.642</td>
</tr>
<tr>
<td>ML COP (II)</td>
<td>0.001*</td>
<td>0.034*</td>
<td>0.796</td>
</tr>
</tbody>
</table>

*, statistically significant at P < 0.05
Figure 4-14: EX versus SI mis-sagittal target reach at fast while sitting - segmental amplitude of AP COP and ML COP excursion; n=6, * P <0.05
Figure 4-15 is a plot of average peak AP COP displacements against peak ML COP displacements across tasks that vary in speed and target locations in the sitting position. The characteristics of this plot were described earlier in Figure 4-10 for the Stand-Reach tasks. Several distinct features can also be observed: (1) There is moderate correlation across tasks for both the EX and SI conditions in the sitting position (r for EX = 0.55, r for SI = 0.65). In contrast with the Stand-Reach tasks, there was also a good correlation between the distance of displacement and the difficulty of the tasks in both the EX and SI conditions. (2) Similar to the Stand-Reach tasks, the slope of the regression line across tasks in the EX condition is also higher than the slope of the regression line in the SI condition (slope for EX = -0.885, slope for SI = -0.434). (3) Both lines almost intercept with the mid-point (0,0) and have no apparent values that lie within the upper right and lower left quadrants in both the EX and SI conditions. (4) The amplitude of the initial peak COP displacement away from the target is also smaller than the amplitude of the end peak COP displacement.

When the individual tasks are averaged, the COP displacement tends to shift toward the ML direction in the SI condition (open symbols are more toward the left on the graph) across all tasks in the sitting position (Figure 4-16). There is a tendency that larger ML COP displacement is associated with the SI condition. Such a trend is most profound in MT reach at fast speeds (solid black versus open black). Due to the minimal displacement, component I COP excursion was more difficult to compare. The range of displacement was significantly smaller in the sitting position than the standing position. Furthermore, reaching at fast speeds was associated with larger peak COP displacements. Reaching at slow speeds is associated with smaller peak COP displacement (blue versus purple and black versus red). Similarly the relationship between the AP COP excursion and ML COP excursion during Sit-Reach tasks also displayed a specific directionality. That is, during reaching with the right arm, backward COP excursion was always associated with excursion to the right and forward COP excursion is associated with the excursion to the left. Therefore COP provides a signature profiles for this task.
Figure 4-15: Comparison between The EX and SI conditions for averaged peak COP displacement during Sit-Reach tasks, a regression interpretation.
Figure 4-16: Averaged peak AP COP versus ML COP displacement during component (I) and component II COP excursion for Sit-Reach tasks for mid-sagittal target and contralateral target at fast and slow speeds.
5 Discussion

The goal of this present research was to determine whether the balance control strategy was the same for the "internally" initiated versus the or "externally" triggered reaching movements. The basic intention was to alter the triggering conditions under which the focal reaching movements were initiated in such a way that motor control strategies used to regulate the posture for the two strategies could be distinguished.

Ideally, the difference in the balance control strategy for the two behavioral conditions can be inferred if the following criteria are met: (1) there is no difference between the executed focal movement under the two behavioral conditions and; (2) the differences of the associated postural adjustments for the two behavioral conditions are measurable by EMG and COP; (3) there are no substantial differences in the body biomechanics at the onset of the focal movement between behavioral conditions; (4) there is a difference in the underlying control strategy between EX an SI behavioral conditions as suggested by Romo and Schultz (1992).

If the demonstrable difference between the two behavioral conditions does not bear out, the context in which the movement is generated may not be important in the CNS control. However, if on the other hand, balance control during reaches is differentiated by how movements are triggered and executed, then the CNS may have two different control strategies for different environmental circumstances.

5.1 Focal Movement Properties in Standing and Sitting

One of the key issues for comparing the balance control strategy between the two behavioral conditions is that if there should be no difference between the physical properties of the arm movements. According to other studies, physical properties or motor performance of the arm movement have been defined as the initial peak velocity or movement time (Benvenuti et al., 1997). Using these criteria, it was found that peak wrist velocity between the two behavioral conditions was similar for reaches to the same target location. Wrist velocity was approximately 3.2 m/second for both the EX and SI conditions during MTf reach, and for the contralateral target was at about 3.8 m/second for CTf reach. These velocities are in agreement with previous velocities for fast paced reaches (Smith, 1993) from this laboratory. Using peak velocity, it was found that focal movement
performance for EX and SI reaches were similar for both fast and slow speeds in both standing and sitting positions.

Although the wrist velocity is generally a good estimate of motor performance, using it as the only parameter may be valid only if a movement can be clearly separated into focal and non focal (postural) components. It is generally agreed upon in the literature that transport andprehension are two discrete phases in reaching. The initial accelerating phase which marks the involvement of the elbow and shoulder to bring the hand close to the object of interest, and the decelerating phase which then marks the braking of the arm concomitantly with finer movements of the hand and finger joints in preparation for target acquisition in the external world have been described by Georgopoulos (1986). In his definition, wrist and shoulder movements were not separated during the first stage. In addition, it has been shown that initial shoulder position influences motor execution. Consequently, the control of the shoulder and the concomitant trunk movements may need to be incorporated into the classification of the “focal movement” for our paradigm as the coordination between the wrist, shoulder and the trunk may be a more suitable “focal movement” measure. Therefore, in this study a change in shoulder position was used as a “surrogate measure” of the trunk movement. The onset latency of the wrist movement was compared to the onset latency of the shoulder movement to examine the coupling characteristics between these two body segments. There was no significant difference between the EX and SI conditions except for reaching at fast speeds while sitting (SMTf and SCTf). However, there seems to be a trend that SI movements involve earlier trunk onsets than the wrist onsets (Figure 4-6). Although the temporal coordination of the wrist and the trunk could vary in the two conditions, it is unlikely that the difference in the balance control seen is due to earlier trunk movement. In summary, regardless of the target locations, during reaches at fast speeds while sitting, trunk movement was initiated earlier than wrist movement under the SI condition. Perhaps the goal of the reaching movement in the sitting position did not have to focus on the “stability” or the “balance” component when the body postures was relatively stable. Instead, the goal could have been to generate a fast movement by establishing a closer body-target distance. In contrast, in the same analyses for the standing tasks and the slow sitting tasks were conducted, no statistical significance difference between the EX and SI conditions were found between the wrist-
shoulder time. Alternatively, one could look at the initial resting COP position to determine if there was a difference in the initial starting position between conditions that could account for the trend observed. The EMG activity demonstrated a change in the underlying muscle activation pattern particularly in the distal lower extremity muscles. For instance, the relative earlier TA onset latency and smaller TA onset magnitude were associated with the SI reaching movements. In addition, to the EMG of TA and med-G muscles, the COP data supported that the EX condition is involved with larger AP COP displacement and whether the SI condition is associated with larger ML COP displacement.

Fast reaching movements have more potential to demonstrate postural differences because they have been reported to require greater acceleration in order to overcome the inertia of the body segments (Horak et al., 1984). In addition, previous studies have shown that slow movements do not elicit postural adjustments prior to focal movements as measured by both EMG and ground reaction forces (Horak et al., 1984; Crenna and Frigo, 1991). In the present study, the associated postural adjustments for EX and SI may involve two separate strategies in balance control of reaching at fast speeds. To demonstrate that the CNS control for EX and SI requires two separate strategies, the effect of multiple velocities on the associated postural adjustments needs to be investigated. If there is no difference in the postural control of the two conditions at slow speeds, then the difference in balance control may be more likely due to the difference in reaching velocities rather than two control mechanisms.

Similar to data reported in previous studies, small accelerations of the limb during reaching demonstrate that distal muscle activity is minimal and highly variable (Horak et al., 1984). In the present study, no significant difference could be measured between EX and SI behavioral conditions. However, when comparing COP characteristics in slow reaches, it was found that during the backward and forward components of the COP excursion, SI reaches are associated with smaller AP COP displacement and larger ML COP displacement for both standing and sitting tasks. This finding is in agreement with the finding in reaching at fast speeds. Therefore, it is postulated that movement under the cued (EX) condition, both while standing and while sitting does not appear to involve the same central control mechanism as that of the internally generated (SI) condition.
5.2 COP Excursion and EMG Profile

As COP represents the point of the resultant ground reaction forces, it varies with the forces generated from the muscle activation required to produce the movement. Consequently, it is highly related to the muscle activity measured by the EMG. In agreement with previous studies, the TA was the muscle group that was activated first prior to the onset of DELT (Smith, 1993). However, in the current paradigm there was a discrepancy in the absolute onset latency in comparison to previous findings in our laboratory. Smith (1993) reported TA onset magnitude to be similar on both sides. The present study demonstrated that TA onset magnitude on the ipsilateral side of the reach was much larger than the contralateral. The difference in the bilateral TA activity is likely due to the rotational requirement of the reach. She also reported that during a MT reaches, ipsilateral TAs were activated at 66 ± 23 ms prior to deltoid onset time. In the present study, it was found that the ipsilateral TA was activated at 165 ± 45 ms prior to deltoid onset. This could be attributed to the younger population with optimal response time in the present study. Reaction time studies could be useful to elucidate this.

Why should there be preparatory TA contractions? The early preparatory activation of the bilateral TAs dorsiflexes the toes and creates pressure on heel. Consequently, the TAs are responsible for the backward COP excursion in the AP direction. This backward shift of COP would exert pressure on the COM posteriorly in order to move it forward to carry out the task. Following the distal muscle activation, the anterior proximal muscles will also contract (Smith, 1993) prior to the posterior muscle activation. When the target is acquired, COP reverses, to the anterior direction in order to decelerate the COM. This is achieved by the contraction of med-Gs (212 ± 34 ms) which would plantarflex the foot and exert pressure in front of the body. In agreement with previous studies, the present results indicated that the interval between the onset of early postural EMG activity (i.e. TA), and early focal EMG activity was shortened when the voluntary reaching was EX (Benvenuti et al., 1997). The onset time of ipsilateral TAs were found to be significantly earlier in the SI condition as compared to the EX condition for fast speed reaches in the standing position. For the MT task, ipsilateral TAs were activated at 164.5 ± 45.1 ms and 353 ± 51.8 ms prior to DELT in the EX and SI conditions respectively (p <0.05) (Figure 5-1). For the CT task, ipsilateral TAs were activated at 172.6 ± 35.9 ms and 376.2 ± 97.9 ms prior to DELT.
Figure 5-1: Onset of preparatory adjustments as measured by the onset of the ipsilateral TA (with respect to DELT) for the Stand-Reach tasks (MTf, MTs, CTf, CTs). * p < 0.05 for comparison between EX and SI n = 6 for all task except for CTs task in the SI condition (**, open circle, n=4)

in the EX and SI conditions respectively in CTf (p <0.05) (Figure 5-1). However, there were no significantly differences found during reaches at slow speeds in the standing position. Onset time analysis of TAs were not carried for the sitting paradigm as they were not the indicative muscle group for postural control during reaches.

This finding suggests that the CNS can vary the timing of postural and focal activation to cope with differences in the instruction. In the EX condition, priority apparently was given to shortening the time between the focal movement, and postural activity. In contrast, the control strategy for the SI condition prioritized the lengthening of
the time between the posture activation and the focal movement activity thus to initiate postural activity earlier. The earlier activity in TA in the SI condition as compared to the EX condition may provide the evidence that a different control strategy (earlier postural activation) might be used in the two conditions. The consequence of which could be that in the SI condition, the longer duration between the postural activity and the focal movement is to initiate preparation of postural adjustments early and thus to increase stability to compensate for the internally generated perturbation during upper limb movement.

In addition, since TA is mainly responsible for the AP COP excursion during reaching while standing, any change in activation pattern of TAs should reflect the changes in the balance control of the AP direction. In the present study, earlier onset time and smaller onset magnitude of TA in the SI condition along with a resultant smaller AP COP displacement and larger ML COP displacement in both component I and component II could support the generation of separate motor strategies for the two behavioral conditions.

A change in the frame of reference for the EX and SI conditions could be one possible explanation. In the present experiment, a change in muscle activity and the resultant COP excursion between the two conditions could result from a different emphasis on the focal movement as compared to the postural components during this reaching task. Massion (1992) has suggested that postural adjustments during task execution might constitute an inherent part of a motor command generated by a hypothetical controller. This hypothetical command is later transformed (processed), giving rise to commands to individual joints. Classification of the joints into “focal” and “postural” may be manufactured by the experimenter but not be inherent in the central nervous system. Alternatively, commands to postural muscles may be closely tied to commands to focal muscles. Thus, postural adjustments are not separate “voluntary motor command,” but inherent components of the overall command. In our experiments, despite the same focal movement properties, different postural adjustments were executed for the EX and SI conditions. Accordingly, the controller could be influenced by the behavioral conditions rather than the focal movements (Massion, 1992). Therefore, the present results could be interpreted such that reaching under the EX and SI conditions might involve two different sensory motor transformations.
A motor program has often been characterized as a set of neural commands directed towards a specific goal. SI movements, not constrained by specific cues or restrictions, are a fundamental balance control strategy. In the SI condition, if stability is foreseeable or required, it is logical to expect that balance or stability becomes a number one priority as long as the task performance does not suffer. In order to test this hypothesis, the focal task must be carried out with optimal performance so that the influence of the behavioral conditions on the balance control can be assessed (i.e. in a more complex task that require the transfer of the COP to the contralateral side at fast speed (CTf)). It is interesting that we found that the difference of the peak COP displacement in the AP and the ML directions between conditions is the greatest in CTf. The complexity of the increased contralaterality and velocity appears to magnify the EX and SI difference (Figure 4-10).

Another possible approach to “tease out” the importance of the change in postural strategy between The EX and SI conditions could be block of the peroneal nerve to inactivate the TA. The consequence of TA inactivity during reaches while standing with no change in postural strategies (no change in the emphasis of AP COP to ML) might be falling or instability in the EX condition but not in SI. Interestingly, Smith (1993) observed that patients following stroke used more hip movement to compensate for the lack of distal muscle activity while reaching. In the present study it was found that low TA activation was associated with COP displacement in the ML direction. The postural strategy could switch from an ankle strategy to hip strategy thus resulting in more ML COP and less AP COP. If this interpretation is correct, the decreased TA and med-G activity and resultant decreased AP displacement and increased ML displacement could suggest that the balance component is likely to be in the ML direction and the task component is in the AP direction. This could parallel what is reported in the stepping paradigm in which the balance component and the task component are more discretely defined in the directionality of the COP excursion (Maki and Mcllroy, 1996).

Previous studies on experimental animals and humans have already shown that there are modifications in the timing and scaling of the postural EMG patterns when the properties of focal movements, and the postural constraints are altered. These modifications had been interpreted as a result of short-term learning or interactions between the central synergy and the peripheral feedback. To demonstrate that the two
behavioral conditions were not due to motor learning, subjects were allowed enough practice trials under both conditions so that they were familiar with the tasks. Therefore, the different EMG patterns and COP characteristics during various reaching tasks (varying speeds, target locations and body positions) was not perceived to be due to motor learning. There is no evidence for adaptation throughout the trials during the experimental period.

One could also speculate that the balance control associated with focal movement is not generated by a single pre-wired network but by two or more such networks which require central commands to deal with an defined relationship amongst networks. Although it is not directly demonstrated in the present study, other studies involving single cell recording have suggested that coordination among multiple networks could indicate task specificity of motor actions. Such coordination between networks should also specify the difference between the EX and SI conditions (Romo and Schultz, 1992). This notion of different motor control strategies between conditions is supported by the high correction across tasks between the peak AP COP displacement and peak ML COP displacement ($r=0.98$ for EX and $r=0.97$ for SI) (ranging from simple to complex, MTs to MTf to CTs and to CTf) while standing (Figure 4-10). There are several possible explanations for these observations; (1) There is a positive relationship between the peak AP COP and ML COP displacement during reaching for both sitting and standing, i.e. a large displacement in the AP direction is associated with a large displacement in the ML direction. The placement away from the origin along the regression line may depend on the nature of the task. This could suggest that there is a possible control center for changing the amplitude or the “gain” of postural adjustments of both AP COP and ML COP displacement simultaneously. And this relationship between the displacement of COP in AP and ML direction are tightly controlled ($r = 0.98$); (2) Postural adjustments take into account the nature of the task (past experience, complexity, speed, target location and body positions) and perhaps with an extensive integration in the CNS to generate an appropriate output command. Such integration could possibly tune for the “gain” of the postural adjustments in similar movements such that the “gain” varies accordingly to the specificity of the task. This could account for the fact that COP displacement for the CTf data is further away from the origin than the MTs (Figure 4-11, Figure 4-16); (3) Normal control of postural adjustment (displacement of COP) during a reaching movements is reproducible and
specific. For example, there is a zone where there is no COP displacement for these reaching movements. In other words, the path of COP excursion is stereotypically backward and lateral, followed by forward and contralateral for a right-handed reach. This relationship in the directionality of postural control is precisely controlled; and (4) A distinguishable COP slope of the regression line for the peak COP displacement for each condition suggests that there are two strategies of postural adjustments. In the case of Stand-Reach tasks, the negative slope for SI is 0.78 and the negative slope for EX 1.18 (Figure 4-10). Slope measures the relationship between the relative change of the independent and dependent variables. The lower incline in slope in SI would indicate a larger preference for ML COP displacement. A similar trend is also seen in the Sit-Reach tasks although not as significant (r for EX is 0.55, r for SI is 0.65). This evidence indirectly suggests that CNS control movements can vary according to the behavioral conditions.

5.3 “Self-Initiated” Paradigms

Benvenuti et al., 1997 investigated anticipatory postural adjustments of rapid arm flexion and extension under the EX and SI conditions in normal subjects. However, due to technical difficulty, they specifically instructed their subjects to wait for three to four seconds before movement execution after seeing the illumination of the light cue. There were two apparent pitfalls by using this approach. The first was, “were the subjects really using an SI strategy when they waited for a delay of 4 seconds to respond and counted off seconds before initiation of their movement?” The counting process could act as strong internal cue. Whether this will result in a different movement execution is unknown. However, it is evident that there is neuronal activity associated with mental rehearsal (Roland et al., 1982). Some authors have even suggested that “thought is action” (Gurd, 1993). It is difficult to prepare a pure SI paradigm. A SI paradigm should eliminate all possible “extra” thought processes related to the upcoming movement. It has been suggested such internal triggering could possibly be in the SMA or other prefrontal structures, but there is also evidence that these are not the only structures to elicit internal commands (Romo and Schultz, 1992). In any experimental condition, one can only minimize the “noise” from the mental rehearsal process. In fact, mental rehearsal may be an embedded fundamental property of the internally-generated or SI movement. Deecke
(1996) differentiated SI from EX movements in the context of the action, action as out of one’s free will and reaction as a response to stimuli from the external environment.

Externally triggered is defined as the illumination of a short pulse of light and “SI” is referred to an event that does not involve a visual cue. The goal of the present study was to minimize cueing in the SI condition. One would speculate that the Benvenuti’s counting process during the course of 4 seconds would contaminate the signal in the CNS and provide addition information for the SI event. In contrast to Benvenuti et al. (1997) approach on SI movements, data was collected in a “continuous” mode with multiple reaches over a prolonged data collection period. Subjects were specifically instructed to restore their posture to the original stance with equal weight distributed through their feet bilaterally before the initiation of the next reach in order to minimize inter-trial differences in initial posture. In addition, subjects were also instructed not to lean towards the target before the reach. Our paradigm with a series of non-rhythmic reaching movements should better reflect the difference in the postural control in the EX and SI.

5.4 Sitting Does Not Equal Standing

The postural control or balance control during reaching in the standing position is different from that of the sitting body position. The obvious difference was the muscle activation pattern. However, there was still some unexpected activation of the distal muscles (TAs and med-Gs). In fact, prior to the experiments it was questioned whether there should be any distal muscle activation in sitting because of stable body position in sitting. As expected the amplitude of COP displacement was significantly smaller in the sitting position (Figure 4-10, 4-15). Two-way ANOVA comparing initial body position In contrast to standing, COP onset latency for reaching while sitting occurred concurrently or later than the onset of the focal reach. Therefore, in the existing stable sitting position, disturbances created by upper extremity movements were smaller and there was small requirement for preparatory postural adjustment to minimize the potential instability. However, varying patterns of trunk flexor and extensor EMG have been shown for reaching movements to different target location to auditory cue (Tyler and Hasan, 1995). These authors found that there were no trunk muscles activities to counter act postural disturbances at the initiation of reaching movements across all target directions.
The obvious difference in COP excursion pattern and distal muscle recruitment pattern between sitting and standing could indicate that postural control for reaches in the sitting position and in the standing position do not involve the same strategies. This could have meaningful consequences for rehabilitation strategies directed towards motor recovery / functional recovery of the postural adjustments during voluntary movements post stroke. A strategy for in the sitting should not be considered the same as one for the standing position. In other words, methods for promoting the motor function while sitting should not be seen as the precursor of the similar motor functions in the standing position. Training for the postural control during reaching in the sitting position post stroke have an independent focus from the standing position because they not comparable.

Table 18: Two-way ANOVA to Compare Initial Body Position and Target Location During Reaches for COP Displacements

<table>
<thead>
<tr>
<th>Position</th>
<th>Target</th>
<th>AP COP Onset Time</th>
<th>ML COP Onset Time</th>
<th>AP COP (I)</th>
<th>ML COP (I)</th>
<th>AP COP (II)</th>
<th>ML COP (II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand vs. Sit</td>
<td></td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>MT vs. CT</td>
<td></td>
<td>NO</td>
<td></td>
<td></td>
<td>NO</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* statistic significance at P < 0.05
NO, non statistically significant at P < 0.05

5.5 Conclusion

It appears that there are separate strategies for balance control which vary with the cue conditions. One cannot rule out that these findings are simply two selected components on a continuum of multiple executions with slight differences due to external or internal context requirements. However, based of the following findings I am proposing that they are separate conditional postural strategies because of the following findings.

- Smaller distal muscle activation pattern, particularly in the TAs, and med-Gs is associated with SI condition as compared to EX condition.
- Smaller peak COP displacement in the AP direction and larger peak COP displacement in the ML direction is associated with SI condition as compared to EX condition.
- Earlier onset time for the postural activity with respect to the onset time of the focal movement is associated with SI condition as compared to EX condition.

- Correlation between peak AP COP and ML COP displacements across tasks demonstrated that SI condition is associated with smaller slope as compared to EX condition.

In conclusion, the difference in the EMG pattern and the slopes of the peak COP displacement for the multiple tasks favors the view that the CNS computes specific postural motor commands that takes into account the context in which the reaching movement is performed. Varying timing of postural muscle activity to cope with differences in the two behavioral conditions is evident. Reaches during the EX condition focus on shorting the latency to onset of the focal movement, which may imply that postural activity is delayed. However, reaches during the SI condition show a lengthening of the latency between the posture activities and the onset of the focal movement implies that the postural activity is initiated earlier. The consequence of earlier postural activation could be increased stability. EX and SI behavioral conditions may involve two separate motor control strategies constructed by the central nervous system that work in parallel the former for reaction the later for action. Alternatively, if human postural responses are similar to subhuman primates reaches, differences in postural control mechanisms during reaches as seen in the present study may indicate that the generation of motor commands for the EX and SI conditions may involve separate neural networks.
6 Summary and Conclusions

1. The kinematics properties, postural EMG profiles and ground reaction forces of six normal subjects were characterized in the context of a visually cued reaching task in both standing and sitting body position to address the question, “Does the center of pressure (COP) excursion and the underlying postural muscle activation pattern relative to the onset of the primary mover (DELT) differ if a rapid reaching movement is EX or SI?”

2. No difference in peak wrist velocities is observed between EX and SI behavioral conditions of the reaches in all tasks which vary in target location and reaching speed. This supports the first hypothesis that the differences in spatial and temporal EMG patterns and COP excursions are due to the behavioral conditions and not to the difference of characteristics of the focal reaching velocity (Figure 4-3).

3. De-coupling of the onset latency of the wrist and the shoulder during SI reaches was evident although not statistically significant at the p < 0.05. SI reaches while standing and while sitting tend to have earlier shoulder movement onset latencies relative to the onset of focal muscle (DELT) (Figure 4-6).

4. The underlying muscle activity, especially the lower distal muscle activation (bilateral TA and bilateral med-G), demonstrated that EX and SI reaches might involve different control mechanisms. Along with earlier onset latency for bilateral TAs, the onset magnitudes for bilateral TAs were also found to be significantly lower in the SI condition. Perhaps, a strategy change had occurred in the SI behavioral condition and a “trade off” of bilateral TA activities for activation a different muscles responsible for a medial-lateral weight shift has occurred.
5. The AP COP and ML COP onset latency relative to the onset of the focal muscle activity was earlier in the SI condition as compared to EX condition for the standing body position. However, only ML COP showed earlier onset latency in the sitting body position.

6. Data support the third hypothesis that earlier onset latency of the lower distal muscles and earlier onset latency of the COP excursion. This may suggest that preparatory postural adjustments associated with reaching movements were executed earlier in the SI behavioral condition than the EX behavioral condition, perhaps for increased stability.

7. COP displacement data suggested that there was a differential weight for directionality of COP excursion. SI reaches were associated with smaller COP excursion in component I (backward) and component II (forward) in the anterior-posterior direction and larger COP excursion in the medial-lateral direction. This observation is more profound in the sitting position than in the standing position. Therefore, SI reaches seemed to emphasis more medial-lateral body weight distribution than the EX condition. Under the non-constrained or preferred behavioral condition (SI), a challenging dynamic reaching task which requires movement of the center of mass to the edge of support will most likely favor the balance component over task component. From the finding that there is more emphasis of COP in the medial-lateral direction one could postulate that the medial-lateral COP excursion relates to the balance adjustment and the anterior-posterior excursion the task execution in this dynamic reaching movement but further studies are required.

8. Difference in lower extremity EMG pattern and COP excursion between SI reaches and EX reaches are direction specific with more difference observed in the reaches across midline (contralateral target).
9. Results derived from EMG profiles and the ground reaction forces demonstrated that the postural adjustments associated with rapid reaching movement in the standing position are different from sitting position. Therefore, rehabilitation strategies for movement retraining post stroke should not use the recovery of motor function in the sitting position as a precursor for the recovery of motor function in the future standing position.
7 Issues for Further Consideration

7.1 Experimental Limitations

It is of primary importance that the numbers of subjects be increased in order to confirm that the associated postural adjustments during rapid reaches for the EX and SI conditions involve two different CNS controls. Although the method of data collection during the non-constrained or SI conditions have been improved as the subjects did not have to wait for a brief period of time before movement execution, there is still an associated limitation. Prior to movement execution, subjects were instructed not to lean forward in any direction. In about twenty percents of the trials for every task the subjects showed a forward lean. From COP data in time domain, it is seen that the excursion is forward and then backward and again forward peaking at target acquisition. In other words, instead of the discrete two components in the COP profile, the prior forward lean introduces a new earlier component. One possible resolution of this problem is to introduce a longer training period (practice 20 trials instead of 5 trials) and allow the subjects to get more familiar with the paradigm. Alternatively, real time processing of ground reaction forces to center of pressure during the data acquisition could be used to discard aberrant trials, however, prolong the experimental period which is usually not feasible.

7.2 Physiological Considerations

One of the key findings of this study is the “trade off” of the AP COP excursion for the ML COP excursion in the SI behavioral condition. Because ground reaction forces are ultimately the outcome of multiple muscle activation, an increased ML COP excursion would imply that there is increase activity in those muscle responsible for ML weight transfer. However, the most important underlying muscle activities contributing to ML transfer were not assessed during the experiment. To further strengthen the observation that SI is not involved more with ML COP excursion, activities of those muscle groups that normally contribute to medial-lateral weight shift, like gluteus medius or tensor fascia latae should be thoroughly quantified.

It would be of utmost importance to test the findings on the different strategies involved with EX and SI behavioral conditions on the stroke population in order to assess
the relationship between the site of lesion and strategies for movement initiation. One of the most crucial findings to be tested is the trend of COP excursion in the AP direction for the COP excursion in the ML direction in the SI condition. It has been reported that COP is predominately placed over the non-paretic limb during quiet standing post stroke; and during dynamic movement it was also found that there is minimal COP excursion toward the paretic side (Smith, 1993; Verrier, 1997) It is rather interesting to see how stroke patients carry out SI reaching movements with emphasis on the medial-lateral COP excursion over anterior-posterior COP excursion. With a decreased TA activation in the paretic side post stroke it would be interesting to determine if they have a similar ML COP trade off.
8 REFERENCES


finger-thumb grasp. Journal of Neurophysiology, 55(6), 1407-1423


reaching tasks after stroke, a random controlled trial. Stroke, 28, 722-728.

Cognitive Brain Research, 59-64.

prehension movements. Experimental Brain Research, 110, 265-278.

predictable in time or voluntary triggered unloading in man. Experimental Brain
Research, 60, 330-334.


unrestricted reaching to targets in contralateral and ipsilateral visual space.
Experimental Brain Research, 60, 159-178.

guided reaching: hemispheric differences in the nature of the deficit. Experimental
Brain Research, 72, 425-435.

Therapy, 70, 855-863

voluntary arm movements 1. Electromyographic data. Journal of Neurology,
Neurosurgery, and Psychiatry, 47, 611-622.

adjustments associated with rapid voluntary arm movement. II. Biomechanical

associated with arm movements during balancing on unstable support surface.


Neuroscience, 5, 776-794.


9 Appendix (I): Subject Consent Form and Information Sheet

* As the control studies for the following Protocol #3192 (stroke studies)
  all normal subjects signed the following consent form with a clear explanation that only
  the laboratory posture of testing was to be conducted (see page 91).
Characteristic Abnormalities in Posture and Upper Limb Control in Patients with Hemiplegia
(Balance Control of Externally-Triggered and Self-Initiated Reaching Movements in Healthy Individuals)

Investigators: Professor Molly Verrier (Chair, Graduate Department of Rehabilitation Science, University of Toronto); Dr. William McIlroy (Professor, Graduate Department of Rehabilitation Science, University of Toronto); Dr. Frank Silver (Director of Acute Stroke Investigation Unit, Toronto Hospital - Western Division); Dr. Cheryl Jaigobin (Stroke Fellow, Toronto Hospital - Western Division); Shelly Sharp (Clinical Resource Specialist in Neuroscience, Toronto Hospital - Western Division); Professor Joanne Howe (Department of Physical Therapy, University of Toronto); Heather Flett (4th year Physical Therapy student, University of Toronto), Joe Lin (Graduate Student, University of Toronto)

PATIENT INFORMATION SHEET

As a patient of the Stroke Program under the direction of Dr. Frank Silver (416-603-5416) at the Toronto Hospital - Western Division, you are being asked to participate in this study which examines balance during reaching. It will be conducted at the University of Toronto and The Toronto Hospital - Western Division under the supervision of Professor Molly Verrier (Director, Restorative Motor Control Laboratory, Graduate Department of Rehabilitation Science, 416-978-5935), in conjunction with Mr. Joe Lin (Graduate Student, Department of Physiology, 416-978-5837) and Ms. Heather Flett (4th year Physical Therapy Student, 416-593-6748) at the University of Toronto.

The purpose of the study is to help in the understanding of the changes that occur in balance while sitting or standing following a stroke.

The study consists of two parts. As a participant in this study, you will be asked to undergo clinical and laboratory tests of balance on five occasions over a four month period.

The clinical tests which includes the Chedoke-McMaster Stroke Assessment, Sitting-Balance Scale, Berg Balance Scale, and Functional Reach will be conducted by Ms. Heather Flett (4th year Physical Therapy student) under the supervision of Ms. Shelly Sharp (Clinical Resource Specialist in
Neuroscience) at The Toronto Hospital - Western Division and later when you are discharged at the rehabilitation facility where you will be staying. These clinical tests will take approximately 1 to 1.5 hours. These tests are done by physical therapists to determine motor and neurological status as well as functional and balance abilities. During testing, subjects will be closely supervised, the investigator will act as a spotter to the patient.

* The laboratory balance measures will be conducted in two phases. You will wear shorts during both phases. In phase one, while you are not able to stand, you will be asked to do the sitting-balance test on a raised stool with a supporting back at The Toronto Hospital - Western Division. In phase two, when you have recovered enough to stand for at least 60 seconds without assistance, you will be asked to do the standing-balance test and the sitting-balance test in the Restorative Motor Control Laboratory at the University of Toronto.

While standing and/or while sitting on a raised stool over two force platforms which measure weight bearing, small surface electrodes will be taped to the skin over the muscles of your legs, arm, trunk and area around the eyes. These surface electrodes are used to monitor muscle activity. They are non-invasive and will not cause any discomfort. Three markers will also be taped to the skin near your ear, shoulder, and wrist. These are used to measure the position of your arm. You will be asked to lean in different directions. You will also be asked to reach forward with your arm to touch a target at a comfortable speed. During the experiment, your safety will be assured by a laboratory assistant at all times.

Risk

The risks to you as a participant in this study are minimal. They are no more than may be incurred during a routine neurological examination or physical therapy assessment. As with any type of balance test, there is a risk of losing your balance and potentially falling. To minimize this risk, you will be closely monitored and a spotter will be present for all balance tests. Your arms and legs may feel tired at the end of the testing session, but if you become tired you will be encouraged to rest during the test. You can also develop a slight rash on your skin in response to the electrode placement; however, this is unlikely.
Benefits

There will be no direct benefit to you for participating in this study. The tests will help you to understand more about your ability or inability, to control your balance and to reach forward both in sitting and standing. However, they will not help to improve your recovery. A copy of the laboratory results will be mailed to you as soon as it becomes available.

Confidentiality

Your personal identity will remain confidential and will only be known to the investigators involved. For the purpose of discussion or publication, an identification number will be used to identify patients. In order to study your postural movement more thoroughly, a video camera will be setup for during the laboratory experiment. These videos are for use in the research setting only and will be kept confidential. At some point during the study, we may review your hospital chart to gather any relevant information including your age, height, weight, current and past medical history, your social status (dwelling, with whom you live with, hobbies, occupation), operative procedure, and results of any test you have undergone (CT scans, blood work and etc.)

If you agree to participate in this study, you have the right to withdraw at any time if you choose. During the clinical or laboratory tests, you may also stop testing at any time by simply stating your wishes to the examiner. This will not influence your care at the hospital. You are also free to ask questions about the procedures throughout the testing period.

Travel tests from your rehabilitation facility to the Restorative Motor Control Laboratory (256 McCaul Street, Toronto, M5T 1W5) at the University of Toronto by taxi will be provided by the investigators.

If you have any questions you may contact Professor Molly Verrier or Mr. Joe Lin at (416) 978-5837. We will answer any of your questions.
SUBJECT CONSENT FORM

This study is titled Characteristic Abnormalities in Posture and Upper Limb Control in Patients with Hemiplegia (Balance Control of Externally-Triggered and Self-Initiated Reaching Movements in Healthy Individuals). It will be conducted at the Toronto Hospital - Western Division and at the University of Toronto under the supervision of Professor Molly Verrier (Director, Restorative Motor Control Laboratory), in conjunction with Mr. Joe Lin (Graduate Student, Department of Physiology) and Ms. Heather Flett (4th year Physical Therapy Student) at the University of Toronto.

The purpose of the study is to help understand the changes that occur in balance while sitting or standing after a stroke. This may help to develop better rehabilitation programs.

I have read the attached Patient Information Sheet.

As a participant in this study, I will be asked to do tests that require me to lean and reach. I will also be asked to perform several clinical tests. I will be tested up to five times over a period of four months.

I agree to be videotaped throughout the study. It has been explained to me that these videos are for use in the research setting only.

I agree that the clinical testing will be conducted by Ms. Heather Flett at the Toronto Hospital - Western Division and following hospital discharge at the rehabilitation facility where I will be staying. I also agree to participate in the balance and reaching testing conducted by Mr. J. Lin and Professor M. Verrier at the hospital and in the Restorative Motor Control Laboratory at the University of Toronto.

It has been explained to me that I may ask questions about the study throughout the testing period. My name will not be used in any publication or discussion about this study, and that all information about me will remain confidential. I understand that my study or discontinue participation at any time will not affect my current or future care at the Toronto Hospital or at the rehabilitation facility in any way. If I have any further questions I may contact M. Verrier or J. Lin by phone at (416) 978-5837.

I consent to participate in this study dated:

_____________________________ ,1997

Name of Participant

_____________________________

Signature, Participant

_____________________________

Name of Witness

_____________________________

Signature, Witness
Appendix (II): Relative EMG Onset Time (to deltoid) and 100 ms Onset Magnitude
Externally-Triggered vs. Self-Initiated; Stand-Reach, MTs
Relative EMG Onset Time (to deltoide) and 100 msec Onset Magnitude

EMG Onset Time (0 msec = deltoide onset)

100 msec Onset Magnitude
Externally-Triggered vs. Self-Initiated; Stand-Reach, CIf
Relative EMG Onset Time (to deltoid) and 100 msec Onset Magnitude

EMG Onset Time (0 msec = deltoid onset)

100 msec Onset Magnitude

Muscle
Group Average

Subject #8
Subject #5
Subject #4
Subject #3
Subject #2
Subject #1

Events and Muscle Groups

Time (msec)
(0 msec = deltoid onset)

Group Average

Magnitudes (uV/msec)

---

---

---

---

---

---

---

---
Externally-Triggered vs. Self-Initiated; Stand-Reach, CTs
Relative EMG Onset Time (to deltoid) and 100 msec Onset Magnitude

EMG Onset Time (0 msec = deltoid onset)

100 msec Onset Magnitude

Muscle Group Average

Subject #3
Subject #4
Subject #5
Subject #6

Group Average

Subject #2
Subject #3
Subject #4
Subject #5

Externally-Triggered Reach
Self-Initiated Reach
Externally-Triggered vs. Self-Initiated; Sit-Reach, SMTf
Relative EMG Onset Time (to deltoid) and 100 msec Onset Magnitude
Externally-Triggered vs. Self-Initiated; Sit-Reach, SMTs
Relative EMG Onset Time (to deltoïd) and 100 msec Onset Magnitude

EMG Onset Time (0 msec = deltoïd onset)

100 msec Onset Magnitude

Muscle
Group Average

Subject #6

Subject #5

Subject #4

Subject #3

Subject #2

Subject #1

Externally-Triggered Reach
Self-Initiated Reach
Externally-Triggered vs. Self-Initiated; Sit-Reach, SCTf
Relative EMG Onset Time (to deltoid) and 100 msec Onset Magnitude

EMG Onset Time (0 msec = deltoid onset)

100 msec Onset Magnitude

Muscle Group Average

Subject #6

Subject #5

Subject #4

Subject #3

Subject #2

Subject #1
Externally-Triggered vs. Self-Initiated; Sit-Reach, SCTs
Relative EMG Onset Time (to deltoid) and 100 msec Onset Magnitude

EMG Onset Time (0 msec = deltoid onset)

100 msec Onset Magnitude
11 Appendix (III): Relative Onset and Peak Times of COP Excursion
Externally-Triggered vs. Self-Initiated; Stand-Reach, MTf
Relative Onset Time & Peak Times of COP Excursion

Anterior-Posterior Direction

Medial-Lateral Direction
Externally-Triggered vs. Self-Initiated; Stand-Reach, MTs
Relative Onset Time & Peak Times of COP Excursion

Anterior-Posterior Direction

Medial-Lateral Direction
Externally-Triggered vs. Self-Initiated; Stand-Reach, CTf
Relative Onset Time & Peak Times of COP Excursion

Anterior-Posterior Direction

Medial-Lateral Direction
Externally-Triggered vs. Self-Initiated; Stand-Reach, CTs
Relative Onset Time & Peak Times of COP Excursion

**Anterior-Posterior Direction**

- **Group Average**
- **Subject #6**
- **Subject #5**
- **Subject #4**
- **Subject #3**
- **Subject #2**
- **Subject #1**

**Medial-Lateral Direction**

- **Group Average**
- **Subject #6**
- **Subject #5**
- **Subject #4**
- **Subject #3**
- **Subject #2**
- **Subject #1**
Externally-Triggered vs. Self-Initiated; Sit-Reah, SMTf
Relative Onset Time & Peak Times of COP Excursion

Anterior-Posterior Direction

Medial-Lateral Direction
Externally-Triggered vs. Self-Initiated; Sit-Reach, SMTs
Relative Onset Time & Peak Times of COP Excursion

Anterior-Posterior Direction

Medial-Lateral Direction
Externally-Triggered vs. Self-Initiated; Sit-Reach, SCTf
Relative Onset Time & Peak Times of COP Excursion

Anterior-Posterior Direction

Medial-Lateral Direction
Externally-Triggered vs. Self-Initiated; Sit-Reach, SCTs
Relative Onset Time & Peak Times of COP Excursion

Anterior-Posterior Direction

Medial-Lateral Direction
12 Appendix (IV): Segmental COP Excursion Amplitude
Externally-Triggered vs. Self-Initiated; MTf
Segmental COP Excursion Amplitude

**Measure:**
- component (i) amplitude
- component (ii) amplitude

**Anterior-Posterior Direction**

**Medial-Lateral Direction**

- Externally-Triggered Reach
- Self-Initiated Reach
Externally-Triggered vs. Self-Initiated; MTs
Segmental COP Excursion Amplitude

**Anterior-Posterior Direction**

- **Pooled Average**
- **Subject #3**
- **Subject #4**
- **Subject #5**
- **Subject #6**
- **Subject #7**

**Medial-Lateral Direction**

- **Pooled Average**
- **Subject #3**
- **Subject #4**
- **Subject #5**
- **Subject #6**
- **Subject #7**

**Measure:**
- component (I) amplitude
- component (II) amplitude

- **Externally-Triggered Reach**
- **Self-Initiated Reach**
Externally-Triggered vs. Self-Initiated; CTf
Segmental COP Excursion Amplitude

Anterior-Posterior Direction

Medial-Lateral Direction

Measure:
- component (I) amplitude
- component (II) amplitude

Externally-Triggered Reach
Self-Initiated Reach
Externally-Triggered vs. Self-Initiated; CTs
Segmental COP Excursion Amplitude

Measure:
component (I) amplitude
component (II) amplitude

Anterior-Posterior Direction

Medial-Lateral Direction
Externally-Triggered vs. Self-Initiated; SMTf
Segmental COP Excursion Amplitude

Measure:
- component (I) amplitude
- component (II) amplitude

Anterior-Posterior Direction

Medial-Lateral Direction
Externally-Triggered vs. Self-Initiated; SMTs
Segmental COP Excursion Amplitude

Anterior-Posterior Direction

![Graph showing amplitude for different subjects and conditions in the anterior-posterior direction.]

Medial-Lateral Direction

![Graph showing amplitude for different subjects and conditions in the medial-lateral direction.]

Measure:
- component (I) amplitude
- component (II) amplitude

Legend:
- Externally-Triggered Reach
- Self-Initiated Reach
Externally-Triggered vs. Self-Initiated; SCTs
Segmental COP Excursion Amplitude

**Anterior-Posterior Direction**

**Medial-Lateral Direction**
13 Appendix (V): Tabulated Summary of Experimental Results
<table>
<thead>
<tr>
<th>Measurements</th>
<th>Tasks</th>
<th>Externally-Triggered versus Self-Initiated</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Focal Movements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTf/SMTf</td>
<td></td>
<td>- 3.2 m/sec for both behavioral conditions</td>
</tr>
<tr>
<td>CTf/SCTf</td>
<td></td>
<td>- 3.8 m/sec for both behavioral conditions</td>
</tr>
<tr>
<td>MTs/SMTs</td>
<td></td>
<td>- 1.9 m/sec for both behavioral conditions</td>
</tr>
<tr>
<td>CTs/SCTs</td>
<td></td>
<td>- 2.2 m/sec for both behavioral conditions</td>
</tr>
<tr>
<td><strong>Coupling between Wrist and Shoulder</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- There is no difference in peak wrist velocity between behavioral conditions; however, contralateral reach is significantly faster than mid-sagittal target reach</td>
</tr>
<tr>
<td><strong>EMG</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Although there is no significant difference, self-initiated reaches tend to have earlier shoulder movement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Distal lower extremity muscle activity is the most indicative measurement to demonstrate the difference in postural control during reaches under externally-triggered and self-initiated conditions.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Onset latency for TAs and med-Gs is earlier in self-initiated condition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 100-ms onset magnitude of TAs is consistently smaller in self-initiated condition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- There is a higher inter-subject variability in reaches at slow speed. No significant difference between behavioral conditions for reaches at slow speed was observed using EMG measurement</td>
</tr>
<tr>
<td><strong>COP Onset Latency</strong></td>
<td>Standing</td>
<td>- COP onset latency for self-initiated reaches while standing is earlier than externally-triggered reaches in both anterior-posterior and medial-lateral directions</td>
</tr>
<tr>
<td></td>
<td>Sitting</td>
<td>- COP onset latency for self-initiated reaches while sitting is earlier than externally-triggered reaches in the medial-lateral direction only</td>
</tr>
<tr>
<td><strong>COP Displacement</strong></td>
<td>Standing (in all tasks)</td>
<td>- AP COP: EX &gt; SI in both backward and forward components</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- ML COP: SI &gt; EX in forward component only</td>
</tr>
<tr>
<td></td>
<td>Sitting (in MTf and MTs only)</td>
<td>- AP COP: EX &gt; SI in both backward and forward components</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- ML COP: SI &gt; EX in both backward and forward components</td>
</tr>
<tr>
<td><strong>COP Ratio: APCOP/MLCOP</strong></td>
<td>Standing (in all tasks)</td>
<td>- Component I: SI ratio &gt; EX ratio</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Component II: SI ratio &lt; EX ratio</td>
</tr>
<tr>
<td></td>
<td>Sitting (in MTf and MTs only)</td>
<td>- Component I: SI ratio &gt; EX ratio</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Component II: SI ratio &lt; EX ratio</td>
</tr>
</tbody>
</table>