Age Differences in the Control of Posture and Movement
During Standing Reach

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Kinesiology)
In The University of Michigan
2009

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To my patients and their families

To my family

Acknowledgements

Thank you to my graduation committee: Drs. Alexander, Ashton-Miller, and Smith for their support and guidance.

Thank you to my doctoral advisor Dr. Susan Brown for being a great mentor in the pursuit of scientific inquiries. It has been a long and arduous journey. Every time I fell off the wagon she never forgot to stop and pick me up. She is always persistent and patient in giving her guidance. Whenever she talks about science, her enthusiasm radiates. She has the amazing ability to make a difficult scientific subject so interesting and simple that probably anyone on the street would be able to understand. Perhaps that is the ultimate learning goal for a doctoral student.

Thanks to the past and present members of Motor Control Lab. Thanks to Dr. Daniel Goble for being a good role model and inspiring researcher. Thanks to Dr. Jeanne Langan, Melissa Wright, and Kathy Kern, for their support and encouragement, especially in the most difficult time.

Thanks to very talented undergraduate students for their assistance in data collection and analysis: Stephanie Huang, Megan Penfold, and Marianne Mousigian.

Thanks to the subjects who volunteered in the experiments.

Thanks to Alex Flick for his help in programming and equipment set-up. Whenever there was a problem during data collection, Alex always responded at the first minute to trouble-shoot. He has also inspired me in learning how to make things work, in addition to thinking how it works.

Thanks to Dr. Wen-Sheng Lin, my husband, for his assistance in programming and resolving technical issues.

Thanks to Kinesiology and Rackham for Fellowships support.

Thanks to Mom and Dad in Taiwan for their love and financial support in furthering my education, enough to buy a house at Arbor Hills.

Thanks to Eleanor and Zachary for successfully delaying my progress in this program. They get up early and go to bed late everyday, despite Zachary's getting full-dose Benadryl occasionally for his allergies. Eleanor, being an over-achieving 2nd grader, frequently reminds me not to quit school and volunteers to baby-sit her little brother so that "Mommy can work on the computer".

Thanks to teachers at St. Paul Lutheran Church Early Childhood Center for providing excellent education for my children so that I can be relived of my motherly duty.

Thanks to my patients and co-workers at Chelsea Community Hospital for their support and encouragement.

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List of Abbreviations

ADLs — activities of daily living

AP — anterior-posterior

APAs — anticipatory postural adjustments

BOS — base of support

CCW — counter clockwise

CEA — control error anomaly

CNS — central nervous system

COG — center of gravity

COM — center of mass

COP — center of pressure

CV — coefficient of variation

CW — clockwise

ML — medial-lateral

Tz — axial torque

Abstract

Age Differences in the Control of Posture and Movement
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Chair: Susan H. Brown

The performance of standing reach requires the maintenance of postural stability and the coordination of multiple joints. Although aging is associated with declines in postural stability, the impact of workspace target heights, reaching with the dominant versus non-dominant arm, and movement context on limb-posture control is not well understood in older adults. The first study of this dissertation examined anticipatory and dynamic postural control during standing reach to different heights with the dominant and non-dominant arm. Compared to younger individuals, older adults produced larger anticipatory postural adjustments (APAs), and center of pressure (COP) trajectories were less smooth, particularly when returning to an upright posture (Chapter 2). These results suggested that older adults used an active “over-control” strategy to increase the safety margin for balance, rather than relying on later, potentially inadequate compensatory postural responses. Older adults exhibited significant increases in APA amplitude and

COP trajectory smoothness when reaching with the dominant compared to the non-dominant hand, perhaps reflecting handedness. In contrast, no differences between age groups were found when examining hand trajectory curvature, indicating that planning of multi-joint, standing reach movements was not affected by age (Chapter 3). Hand trajectories were more curved during reaching to low compared to higher targets regardless of age, suggesting that the biomechanical demands associated with controlling the trunk affects hand trajectory formation. The second study examined whether the movement context (pointing versus grasping) would affect postural control (Chapter 4). In older adults only, grasping was associated with a decrease in COP trajectory linearity, suggesting that aging affects the ability to anticipate and counteract the internal perturbations generated by grasping an object. From a rehabilitative perspective, the results of these studies indicate that standing balance training in older adults should incorporate different workspace locations, functional goals, as well as tasks involving reaching with both the dominant and non-dominant hands.

Chapter 1
Introduction

Tasks that require reaching, such as getting a pot from a cabinet, turning a doorknob, or retrieving a book from a shelf, are commonly performed daily activities. To accomplish reach from a standing position, the central nervous system (CNS) needs to solve two problems pertaining to postural and movement control. First, the execution of reaching movements disturbs postural stability because it alters the body's geometry and results in reaction joint torques. Thus, anticipatory postural adjustments are needed to counter the forthcoming perturbations arising from movement execution (Massion, 1992). Secondly, various joint configuration patterns are available to bring the hand to the target. Despite a high demand for coordinating multiple joints, relatively straight hand trajectories with bell-shaped velocity profiles have been viewed as the constraint utilized by the CNS in planning arm movements (Morasso, 1981). This chapter reviews the literature in the control of posture and arm movements in young and older adults, and specifies the general aims and hypotheses of this dissertation.

Control of Standing Balance

To maintain standing balance, the vertical projection of the center of mass (COM) intersecting the horizontal plane, i.e. the center of gravity (COG), needs to be kept within the base of support (BOS). The range for shifting the COG without changing the BOS corresponds to the stability limits. According to Pai and Patton (1997), stability limits are not determined simply by the geometry of the BOS. For instance, a small forward acceleration of the COM is sufficient to displace it outside the BOS when the COM locates near the anterior boundaries of the BOS. In contrast, a larger forward acceleration of the COM is needed to cause loss of balance if the COM is close to the posterior boundaries of the BOS. Therefore, stability limits should be defined as the combined state of the instant position and velocity of the COM with relation to the BOS.

Stability limits can be estimated by measuring the maximum displacement of the center of pressure (COP), which is the location of ground reaction force vectors on the BOS and reflects the neuromuscular effort in controlling the COG (Winter, 1990). One clinical test to measure stability limits is the forward functional reach test because the extent of reach is correlated with COP maximum displacements during the task (Duncan et al., 1990, 1992). Functional reach has been modified to also include reaching in the lateral and backward direction (Newton, 2001). With age, maximum COP displacements and maximum functional reach distance are decreased, indicating a reduced capability to control the COG movements within BOS (King et al., 1994; Duncan et al., 1990, 1992; Holbein-Jenny et al., 2007).

The difficulty level for maintaining standing balance varies depending on the direction of movements. Newton (2001) reported that during maximum reach in multiple directions in the horizontal plane, older adults had the smallest reach distance in the backward direction. It was suggested that with the position of ankle joint relative to the foot, there is a greater biomechanical advantage for shifting the COP forward than backward during reaching. Newton (2001) also found a significant correlation between the Fear of Falling Index and the backward reach distance, indicating that fear of falls might have contributed to directional differences in the reach distance. Recently, studies have found that the age-related reduction in the maximum reach distance was greater during upward than forward reach (Row & Cavanagh, 2007). Taken together these findings indicate that aging affects the control of standing balance during movements made in different directions and to different heights.

Postural Control Associated with Voluntary Movements

To prevent the position and velocity of the COM from exceeding stability limits, the CNS utilizes feedforward and feedback postural control mechanisms.

Function of anticipatory postural adjustments

Belen'kii et al. (1967) first reported that muscles in the legs and trunk are activated 40 to 60 ms prior to the onset of the prime mover muscles during arm raising movements performed by standing subjects. Subsequent studies documented that consistent patterns of muscle activity or acceleration in the trunk and legs were observed prior to the initiation of rapid arm movements (Bouisset & Zattara, 1981, 1987; Cordo & Nashner, 1982; Horak et al., 1984; Lee et al., 1987). It has been found that these patterns act to move the COM upward and forward. This, in turn, counteracts the backward and downward acceleration of the COM which results from reaction forces of arm movements. Thus, it was proposed that the CNS generates anticipatory postural adjustments (APAs) to stabilize the COM prior to the forthcoming perturbations associated with movements (Bouisset & Zattara, 1987). APAs have also been observed preceding the onset of dropping or lifting a load (Aruin & Latash, 1996; Toussaint et al., 1998), suggesting that the CNS is able to estimate changes in the mass of the system and produces APA to counteract the expected perturbations.

In addition to stabilization of posture, APAs can assist in generating the dynamics required for the forthcoming movements, particularly in tasks involving multi-joint coordination or tasks with a change in the BOS configuration. Stapley et al. (1999) showed that, when standing subjects reached to targets placed in front of their feet, the COM displacements were as large as 90% of the length of BOS. The extent of the COM displacements indicated that APAs did not serve to stabilize the COM, which was contrary to the findings by Bouisset and Zattara (1987). Further, Stapley et al. (1999) found that ground reaction forces and the COP displacement during the APA phase created the angular momentum required for shifting the COM forward toward the reach target. Similarly, APAs during gait initiation generated the momentum required for displaying the COM over the new BOS (Breniere & Do, 1991). Thus, APAs do not solely function to stabilize posture but also contribute to the forthcoming movement dynamics.

Modulation of anticipatory postural adjustments

Numerous studies have examined processes affecting the programming of APAs by analyzing APA amplitudes (changes in the postural muscle activity or the resultant mechanical effects prior to the onset of upcoming perturbations) and APA duration (the interval between the onset of postural and upcoming perturbations).

When the forthcoming perturbations arise from one’s own motor action, APA amplitude and/or duration are scaled with the movement speed or amplitude (Horak et al., 1984; Lee et al., 1987; Mochizuki et al., 2004), or the inertia of the moving body segment

(Bouisset et al., 2000; Horak et al., 1984). Moreover, the patterns of muscle activity vary depending on movement direction (Aruin & Latash, 1995; Leonard et al., 2009). Bouisset et al. (2000) examined whether APA amplitude and duration are scaled identically with the kinetic energy and work of the upcoming arm raising movements made at different speeds, with and without an added load. They found that while both APA amplitude and duration are scaled with the same parameters of the upcoming arm movement, APA duration was more sensitive to the inertia load of the moving arm.

Postural perturbations resulting from changes in the mass of the system can also influence the programming of APA amplitude and duration. Aruin and colleagues examined the modulation of APAs in response to perturbations in a series of studies using unloading task, which required standing subjects to release a load being held in front of them with shoulder abduction movements. Perturbations caused by dropping the load were in the sagittal plane and consequently were not related to the reaction forces induced by arm abduction movements. Aruin and Latash (1996) found that APA amplitudes and duration were correlated with the magnitudes of the load. Later, Aruin et al. (2003) showed that when the load was released by a device triggered with jaw or mouth movements, APAs are diminished. These results indicate that the CNS needs information related to the characteristics of the forthcoming perturbation, possibly via the sensory inputs and efferent copy of motor commands holding the load, in order to appropriately program APAs. More recently, Shiratori and Aruin (2007) demonstrated that while releasing the same load, APA amplitudes were greater at faster movement speeds but remained unchanged with larger movements. Moreover, APAs observed during the unloading task were not present when arm movements were performed without releasing a load. These results together suggest that when the expected perturbations are not directly related to a motor action, APAs are modulated primarily with the dynamics of perturbations and to some extent with the speed of the movements.

Compensatory postural responses

Once movements are initiated, compensatory postural responses are triggered by sensory feedback from externally imposed perturbations. Stereotypical muscle activation patterns have been reported in standing subjects following perturbations to the support surface (Nashner, 1977; Horak & Nashner, 1986). Horak and Nashner (1986) reported that activity first begins in the ankle joint muscles 73 to 110 ms following the perturbation, and then radiates proximally to the thigh and trunk muscles. This pattern, i.e. an ankle strategy, exerts torques at the ankle joint to correct the COM movements. The authors also found that when the standing surface is shorter than the foot length, antagonistic thigh and trunk muscles of those observed in the ankle strategy are recruited in the opposite proximal to distance sequence while the ankle muscles are not activated. They referred to this pattern as hip strategy, which produces movements primarily at the hip joints to restore balance and generates shear force on the support surface but little ankle torque. Moreover, mixed ankle and hip strategy has been noted when the support surfaces are intermediate in length between the shortest and longest in their experiment. When the support surface was changed from one length to the other, muscle activation patterns appropriate for the ankle or hip strategy gradually emerged after subjects performed more practice trials. The above findings indicate that central organization of compensatory postural responses utilizes a limited repertoire of muscle synergies.

Using a similar paradigm of unexpected surface translation, McIlroy and Maki (1993) demonstrated that stepping to recover balance was more frequently observed when subjects were not instructed to keep their feet in place. These results contradict the traditional view of stepping as the last resort to recover balance. They also found that arm muscles were activated with onset timings similar to that seen in the ankle strategy, suggesting that protective arm movements are also functionally important in correcting external perturbations (McIlroy & Maki, 1995).

Anticipatory Postural Adjustments Associated with Handedness

Upper limb asymmetries

Handedness refers to the preferred use of a particular hand to perform skilled movements. Visually guided movements made with the dominant arm are typically associated with shorter duration and more skillful than the non-dominant arm (Annett et al., 1979; Roy et al., 1994; Todor & Cisneros, 1985). Imaging studies have found evidence of structural asymmetry in the cerebral cortex (Amunts et al., 1996; Hervé et al. 2006), brain stem (Anastasi et al., 2006), and cerebellum (Szabó et al. 2003), providing neurophysiological evidence of upper limb asymmetries.

Parallel to the findings of asymmetric hemispheric structure, several studies have reported asymmetric sensory processes between upper limbs. Goble and Brown (2008) examined differences in the ability to utilize proprioception or visual feedback between the dominant and non-dominant arm in right handed individuals. A target angle of the elbow joint was presented by either passively moving the subject's arm to the position or by projecting the position with a circular light in front of the subject. When different sensory information was used to match the target position presented previously, both the dominant and non-dominant arms showed smaller errors with visual and proprioceptive feedback, respectively. These findings may provide support for the advantage of the dominant arm in right handed individuals during the performance of visually-guided functional tasks. Adamo et al. (2009) examined age-related differences in upper limbs proprioceptive acuity using a wrist-position-matching task in right handed individuals. They found that young and older adults showed comparable proprioceptive matching of limb position when matching was performed with the non-dominant hand. Further, differences in matching performance between hands were significantly affected by age. In older adults only, matching errors were significantly increased when the dominant hand was used to match the position presented at the non-dominant hand. The authors suggested that age-related declines in corticospinal control and in interhemisphere transfer of information from the left to right hemisphere may have contributed to the asymmetries in proprioceptive matching observed in older adults.

Dynamic dominance hypothesis

Studies examining arm reaching movements to targets have supported a dynamic dominance hypothesis as the mechanism underlying asymmetric sensorimotor behavior between hands. In a series of targeted arm reaching movements, the dominant arm was found to exploit more reaction joint torques and required smaller shoulder and elbow muscle torques than the non-dominant arm (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000). On the contrary, when a mass was unexpectedly loaded to the arm before movement onset, the non-dominant but not the dominant arm showed comparable final positional accuracy compared to unloaded condition (Bagesteiro & Sainburg, 2003). Moreover, Sainburg and Schaefer (2004) reported that the strategies for scaling movement amplitudes are different during reaching with the dominant and non-dominant hands. When elbow extension movements are made through various ranges of motion, the dominant right hand scales peak acceleration with movement ranges. This strategy primarily depends on feedforward preplanning processes. In contrast, for the left non-dominant hand, the duration of initial acceleration impulse increases with larger movement amplitudes. This strategy is mediated mainly through feedback-based mechanisms.

The above findings support that the dominant arm is specialized in feedforward control of intersegmental dynamics and hence, is more skillful in dynamic movement tasks (e.g. hammering or cutting) (Bagesteiro & Sainburg, 2002; Sainburg, 2002; Sainburg & Kalakanis, 2000; Wang & Sainburg, 2005). In contrast, the non-dominant arm is specialized at feedback-mediated control of steady state posture and impedance during the final phase of reaching movements and consequently, is more proficient at the stabilizing role in the tasks (e.g. holding an object) (Bagesteiro & Sainburg, 2003).

Postural asymmetries

In contrast to upper limb asymmetries, the concept of asymmetric motor function extending to more proximal and body segments has been overlooked. From a phylogenetic perspective, lateralized function of upper limbs should be accompanied with the asymmetrical control of the whole body (MacNeilage, 2006). With the law of physics in action and reaction forces, asymmetric postural control would be expected in order to accommodate asymmetric control of intersegmental reaction forces as suggested by the dynamic dominant hypothesis (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000). Therefore, APAs may be more efficient in counteracting perturbations and generating movement dynamics during visually-guided movements by the dominant than by the non-dominant arm.

Teyssèdre et al. (2000) compared APAs during pointing movements made at maximum speeds with the dominant and non-dominant arm in seated right handed individuals. Difficulty in maintaining balance also depended on whether subjects sat with their thighs fully or partially supported on the chair. They found that in the thigh fully supported condition, APAs began earlier and the movement speed was higher for pointing movements by the dominant arm. In the less stable sitting condition, the movement speed was not different between arms but postural muscles exhibited a higher activation level during non-dominant arm movements. Increased amplitudes of postural muscle activity during non-dominant arm movements parallel previous findings of increased muscle torques during reaching movements made with the non-dominant arm (Sainburg & Kalakanis, 2000; Bagesteiro & Sainburg, 2002). Results from the study by Teyssèdre et al. (2000) suggest that the asymmetry in the parameters of APAs is dependent on the degree of body stability.

Ypsilanti et al. (2009) examined rapid and accurate forward aiming movements to targets within arm's length in right-handed, right-eyed, and right-footed standing subjects. They found that despite comparable movement speeds between hands, the dominant arm movements had a shorter APA duration, a lower endpoint error, and a smaller COP maximum displacement in the medial-lateral direction. They suggested that in the non-dominant arm, longer APA duration reflected a better ability to anticipate perturbations. Increased COP dispersion medial-laterally could result from increased curvature of hand trajectories that disturb the COP.

In studies of gait in right leg dominant adults, Sadeghi et al. (2001) reported that during the stance phase, power generated at the right hip in the sagittal plane contributed primarily to propulsion of gait. In contrast, the majority of power generated at the left hip joint occurred in the transverse and frontal planes and were associated with energy absorption. Therefore, the dominant leg is to move the body forward and the non-dominant leg is to ensure a safe body weight transfer. These findings are in accordance with differential functional roles for the dominant and non-dominant upper limbs in the dynamic dominance hypothesis (Sainburg, 2005). Overall, the dominant arm and leg primarily involve in dynamic movements and the non-dominant arm and leg contribute to the maintenance of posture.

Control of Whole Body Reaching Movements

Invariant characteristics of hand trajectories

Redundancy in the human motor system allows for infinite combinations of joint angles which can be utilized to bring the hand to a target. When reaching movements are performed from a standing position, task complexity is increased as the demand to maintain body stability increases. However, the kinematics of arm movements have traditionally been examined without considering the component of postural control.

Experimental and computational studies in seated subjects have identified stereotypical kinematic features of planar arm movements (Morasso, 1981; Soechting & Lacquaniti, 1981; Flash & Hogan, 1985). Morasso (1981) investigated arm movements made in the horizontal plane between two targets. It was found that while angular displacements of the shoulder and elbow joints varied markedly during movements to different targets, hand trajectories were nearly straight with smooth, single peak symmetrical velocity profiles, similar to what has been seen in single joint movements (Brown & Cooke, 1981, 1990; Cooke & Brown, 1990). These characteristics remain unchanged despite different movement velocities, direction, and amplitudes (Flash & Hogan, 1985; Soechting & Lacquaniti, 1981). When reaching movements are accomplished with trunk displacement, the invariant features of hand trajectories are consistently observed, regardless of the extent and direction of trunk movements (Kaminski et al., 1995; Ma & Feldman, 1995). Since these earlier studies, straight hand trajectories have been viewed as the constraint employed by the CNS in planning arm movements (Gielen, 2009).

Coordination of arm and trunk during reaching

Reaching movements involving the trunk segment demand a higher degree of multi-joint coordination and postural stabilization than reaching with the arms only. Ma and Feldman (1995) proposed that the CNS plans trunk-assisted reaching movements by employing two functionally independent synergies. One coordinates the joints to shift the hand to the target whereas the other coordinates the arm and trunk segments to ensure that the hand trajectories remain unchanged.

It is believed that the arm-trunk coordination synergy is controlled in a feedforward manner to preserve hand trajectories. Bortolami et al. (2008) examined arm reaching movements made to targets with active versus passive trunk rotation elicited by exposing seated subjects to constant rotational velocity in a slowly rotating room. They found that reaching movements made with voluntary trunk rotation were accurate despite significantly greater reaction torques (Coriolis torques) from trunk movements. In contrast, reaching movements made during exposure to passive trunk rotation showed more errors with greater deviations from the targets. Therefore, the effect of trunk movements on hand trajectories is anticipated and compensated for in advance.

The influence of equilibrium constraints on hand trajectories during reaching movements was investigated by Berret et al. (2009) during reaching to targets placed on the ground. They asked subjects to stand on a normal or reduced BOS, or to lock their knees with a normal BOS. In these above conditions, the state of body stability was altered. In the other conditions, they instructed subjects to make a straight versus curved path while standing on a normal BOS. It was found that across different conditions of body stability, the curvature and velocity profiles of hand trajectories were comparable. In contrast, reaching with a curved path significantly increased the COM displacement in the anterior-posterior direction. In accordance with Ma and Feldman's (1995) findings, Berret et al. (2009) also identified two primary joint coordination patterns in these types of tasks with principal component analysis. They found that while one pattern controls the coupling of arm joints and hand trajectories, the other coordinates the legs, trunk, and head to maintain balance. Above findings support the view that the formation of hand trajectories is not influenced by the demand to maintain postural stability. In contrast, curved hand trajectories can result in a larger COM displacement and is detrimental to postural stability.

Age-Related Changes in Anticipatory Postural Adjustments

Age-related changes in anticipatory postural adjustments (APAs) may contribute to deficits in postural stabilization during the performance of voluntary movements. Inglin and Woollacott (1988) examined APAs in standing subjects when they pushed and pulled a handle. They found that older adults had longer APA duration than young adults. Stelmach et al. (1990) adopted the same experimental task and instructed subjects to perform the movements in a reaction time paradigm from a sitting and standing position. They showed that older adults were slower in initiating the movement from a standing position than young adults, suggesting that postural stabilization preceding the onset of movements may become slower with age.

Research examining arm raising movements has shown both normal (Garland et al., 1997) and reduced APA durations (Rogers et al., 1992; Woollacott & Manchester, 1993) in older than young adults. Bleuse et al. (2006) observed that APA durations were reduced in older adults when arm raising movements were performed at maximum speed, whether or not an additional load was added to the arm. At slow movement speeds, older adults showed no impairments in APAs production. Woollacott and Manchester (1993) suggested that inconsistent findings of age-related differences in APA duration may be related to the mechanical characteristics of the forthcoming movement. When the task involved generating force with the arm against a support, older adults required longer time to generate the forces for postural stabilization. In contrast, when free standing subjects performed arm movements without contact with a surface, APA duration was shorter in older adults.

In addition to altered APA duration, the activation patterns of postural muscles and APA amplitudes are affected by age. Inglin and Woollacott (1988) reported that older adults had less consistent patterns in recruiting postural muscles prior to the onset of arm pushing and pulling movements. Moreover, a greater percentage of older adults activated muscles either on both sides of the joints, or only the distal muscles, reflecting a mechanically less efficient strategy. During arm raising movements, older adults were found to more likely recruit the proximal instead of distal postural muscles first or activate the thigh muscles at greater amplitudes (Bleuse et al., 2006). In spite of altered patterns of postural muscle activity, arm movement speeds were not different between groups.

To date, age-related changes in APAs have primarily focused on the analysis of APA duration and spatial-temporal recruitment patterns of postural and prime mover muscles. In contrast, little information is known regarding whether APA amplitude is also altered in older adults.

Age Differences in Reaching Movements

It has been well established that movements slow considerably with age (Salthouse, 1979; Welford, 1984). Numerous studies with seated subjects have identified features of age differences in arm movements, including a longer movement time and deceleration duration profile (Cooke et al., 1989; Goggin & Meeuwsen, 1992), lower peak velocity (Bellgrove et al., 1998), and increased movement trajectory variability

(Cooke et al., 1989; Ketcham et al., 2002; Morgan et al., 1994). On the other hand, age differences in reaching movements involving the trunk and the maintenance of standing balance have rarely been examined.

The ability to coordinate the trunk during multi-joint movements is affected by age. When subjects were instructed to reach maximally from a standing position, the amount of forward trunk flexion and rotation, and maximum reach distances were reduced in older adults (Cavanaugh et al., 1998; Kozak et al., 2003). Smaller angular displacements of the trunk were also observed in older adults compared to young adults during standing to sitting tasks (Dubost et al., 2005). An age-related reduction in trunk movements is likely related to the demand for maintaining postural stability.

In a study by Paizis et al. (2008), young and older adults reached forward to a target on the ground from a standing position. Compared to young adults, older adults showed straighter hand trajectories, smaller hand peak velocities and longer hand movement duration. The COM and COP displacements in the AP direction were reduced with age. With regression analysis, the authors were able to identify the primary joint coordination patterns utilized during the task and found that patterns of joint coupling were not different between groups. It was suggested that older adults made straighter hand trajectories to limit the forward displacement of COM due to movements. In a follow-up control experiment (Paizis et al., 2008), they instructed young subjects to perform the same task while standing on a reduced BOS. With decreased postural stability, young subjects also demonstrated straighter hand trajectories, indicating that the need to preserve equilibrium led to changes in hand kinematics.

Aging and Asymmetric Motor Behaviors

Whether or not aging is associated with increased or decreased asymmetries in upper limb motor behaviors is inconclusive. However, it is possible that long-term preferential use of the dominant limbs may lead to greater proficiency and greater resistance to age-related declines in motor skills.

Studies have reported that differences in motor skills between the dominant versus the non-dominant hand were greater in older than young adults, especially in more complex and fast movements (Weller & Latimer-Sayer, 1985; Mitrushina et al., 1995; Francis & Spirduso, 2000). Mitrushina et al. (1995) found that in a group of right-handed adults aged 60 to 88 years, the extent of slowing of the left hand with advanced age was significant only in tasks requiring the highest level of precision, visual-motor coordination, attention and visual tracking. On the other hand, when older adults became more familiar with the task after more practice (Weller & Latimer-Sayer, 1985), or were given sufficient time to aim for accuracy (Meudell & Greenhalgh, 1987), age differences in asymmetric performance between hands were no longer present.

Teixeira (2007) analyzed manual asymmetry in right handed adults aged 18 o 63 years. The motor tasks were classified into three categories: symmetric performance between hands, inconsistent asymmetry, and consistent asymmetry. Across ages, there was decreased asymmetry for maximum grip strength and increased asymmetry for sequential drawing tasks, suggesting that manual asymmetries are task specific. Kalisch et al. (2006) found that performance differences between hands increased with age during tasks of fast aiming, maintaining a prescribed arm-hand posture, and line tracing, but not during repetitive finger tapping movements. These results supported that the view that the expression of manual asymmetry in older adults is task-specific.

To date, it is now known whether aging is associated with changes in postural asymmetries. Skelton et al. (2002) found that asymmetric muscle power in legs was significantly greater in older adults with a history of falls. Blaszczyk et al. (2000) examined age effects on the vertical forces exerted by each leg during quiet stance. It was shown that asymmetric leg loading was increased with age. Older adults tended to put proportionally more body weight towards one leg compared to young adults, especially with eyes closed. In addition, postural sway in the absence of vision was significantly correlated with the extent of leg load asymmetry, with more unstable older adults experiencing greater differences in load between legs. However, it is not known whether the patterns of asymmetric leg loading are related to leg asymmetries, e.g. more weight on the dominant than non-dominant leg.

Physiological Factors Underlying Age-Related Changes in Postural Control

Age-related declines in sensory, neuromuscular, perceptual, and cognitive function have been implicated in altered postural responses in older adults.

<u>Sensory systems</u>

Numerous studies have documented that impaired balance and/or falls in older adults are related to declines in visual (Haibach et al., 2007; Ivers et al., 1998; Lord et al., 2001; Lord, 2006), somatosensory (Lord et al., 1991, 1999; Menz et al., 2006a; Son et al., 2009), and vestibular function (Kristinsdottir et al., 2001). Although sensory feedback from multiple systems can be used to control posture, age differences in balance are most pronounced when inputs from more than one system are diminished or altered (Bugnariu & Fung, 2007; Hay et al., 1996; Teasdale et al., 1991). In a study by Hay et al. (1996), subjects initially stood with a vibration perturbation applied to the tendon of ankle muscles. Once the vibration was turned off, older adults were not able to take advantage of the reinsertion of proprioceptive inputs whereas young adults quickly integrated proprioceptive inputs to stabilize posture.

Bugnariu and Fung (2007) reported that older adults demonstrated altered postural responses in quiet stance when visual and somatosensory inputs provided conflicting information regarding one's motion in space. When visual field and support surface moved in the same direction, older adults recovered balance by taking more steps, at delayed latencies, and with larger COP and COM displacements. Buatois et al. (2006) found that older adults with recurrent falls were unable to stabilize posture in quiet stance even after repetitive exposure to conflicting sensory inputs. The results suggest that aging is associated with impaired central mechanisms for sensory integration when sensory inputs from different systems provide ambiguous and conflicting information. Older adults are also more likely to stabilize their head position in space than young adults during difficult balance tasks, including movements of the support surface with and without movements of the visual field (Di Fabio & Emasith, 1997). The authors suggested that this head-stabilization strategy reduces the complexity in interpreting information from multiple sensory systems.

Motor system

Studies have attributed age-related declines in leg muscle strength to impaired balance and/or falls in older adults (Era et al., 1996; Daubney & Culham, 1999; Horlings et al., 2008; Lord et al., 1999; Schultz et al., 1997). Binda et al. (2003) examined the relationship between isometric muscle strength and balance control in older adults with and without fear of falls. They reported that hip extensors, knee extensors and flexors, and ankle plantarflexors significantly correlated with maximum COP displacements in the anterior-posterior (AP) direction during a self-initiated maximum leaning task. Similarly, Melzer et al. (2009) reported that the strength of the ankle plantar-flexor significantly correlated with maximum forward COP displacements in older adults.

Using the paradigm of induced falls from a forward leaning position, Wojcik et al. (2001) reported that both young and older adults generated comparable leg joint torques at nearly maximal magnitudes to recover balance. With a similar paradigm, Madigan and Lloyd (2005) found that older adults had smaller peak knee extensor torques when stepping to recover balance. Arampatzis et al. (2008) found that the ability to regain balance with a single step following a forward fall is not related to leg strength and stiffness in older adults. The above results indicate that strength generation capacity of leg muscles is not the only mechanism determining dynamic balance control during stepping responses in older adults.

Perceptual processes

The perception of stability limits during reaching movements may be altered with age. In a study by Robinovitch and Cronin (1999), young and older adults living in the nursing home and participating at day care estimated their maximum forward functional reach distance before executing the task. It was found that older adults with impaired postural stability tended to overestimate maximum reach distance to a greater extent. In contrast, young adults underestimated their maximum reach distance. Therefore, lack of awareness of the decline in stability limits could be related to decreased balance and falls in older adults.

Binda et al. (2003) reported that maximum COP displacement in the anterior, left, and right directions while leaning maximally were smaller in older adults reporting fears of falls compared to older adults who were not fearful of falls. Feldman and Robinovitch (2005) compared whether young and older adults differ in their perceived ability to approach their maximum reach distance. Subjects reached forward as far as possible to grasp a target that was moving back and forth. Older and young adults reached to the target at 65% and 84% of maximum reach distance on the first trial, and at 79% and 89% of maximum reach distance after multiple trials, respectively. Although older adults were able to improve after practice, they were less likely than young adults to approach the target at their limits, suggesting cognitive or motivation factors underlying the differences between perceived and actual ability to shift the COP in older adults.

Summary of Literature Review

This chapter reviewed recent literature in the area of age differences in the control of posture and reaching movements. In older adults, anticipatory postural adjustments (APA) are characterized by altered spatial-temporal activation patterns in postural muscles. Such age-related changes in APA may contribute to difficulties in maintaining dynamic balance during movement execution, such as the reduced capacity to shift the COP maximally during standing reach.

It is well recognized that in planning arm movements, the CNS attempts to produce roughly straight hand trajectories. Even when the trunk is used in the reach, hand trajectories remain straight. When reaching tasks are performed from a standing position, older adults reduce the amount of trunk displacement and alter the straightness of hand trajectories. These age-related changes may reflect a strategy to minimize postural perturbations arising from movements.

It has been well established that sensorimotor performance between upper limbs is asymmetric, particularly in older adults after life-long preferred use of the dominant arm. Recently, studies have found evidence supporting asymmetric organization of postural control associated with movements made by the dominant and non-dominant in young adults.

Thesis Statement

Reaching tasks, particularly from a standing position, are important daily activities that require the coordination of multiple joints and maintenance of postural stability. It is well recognized that aging is associated with declines in both the control of posture (Maki & McIlroy, 2006; Horak, 2006) and goal-directed arm movements (Bellgrove et al., 1998; Cooke et al., 1989; Darling et al., 1989; Pohl et al., 1996). Indeed, in older adults, falls frequently occur during reaching tasks in standing (Nachreiner et al., 2007).

Reaching tasks are commonly made towards various regions in the workspace and involve interacting with objects in the surrounding environment. To date, research examining age differences in posture control during standing reach has employed limited experimental paradigms. APA associated with arm movements have been examined with subjects simply raising the arm up in a forward direction to shoulder height or pushing and pulling a handle. Although older adults reported more difficulties in performing upward- and downward-oriented movements, such as reaching up, stooping, bending and crouching (Ervin, 2006), it is not known whether age-related changes in APA during reaching vary depending on the movement direction. Further, no study has examined age-related changes in APA in addition to dynamic balance during movement execution. Because APA aim to counteract perturbations arising from the forthcoming movements, concurrent analysis of APA and dynamic balance may reveal the effectiveness of APA in stabilizing posture following the onset of movements.

The influence of functional goals of movements on postural control in older adults has not been examined. The challenge to postural control is increased when a manipulation component is required at the end of the reach. Compared to simply reaching forward, the requirement of manipulation following reaching prolongs the time one needs to keeps the COP closer to the boundaries of the BOS. Moreover, the action required following reaching can change the movement context and consequently affects the planning processes of posture and movements. For instance, when the goal of reaching is to turn a doorknob, the CNS also needs to plan postural adjustments associated with the forces arising from interacting with the door. An internal model related to the functional goals and the physical properties of the door is required. In contrast, planning for the additional manipulation component is not necessary during simple forward reaching tasks.

While a stable posture is fundamental to the successful performance of reaching tasks, arm movement control has frequently been examined from a seated position without considering the need to maintain standing balance and to coordinate the trunk with the arm. Whether age-related declines in postural and trunk control affect the formation of hand trajectories is not clear. To what extent the CNS adapts the kinematics of arm movements to fulfill the constraints of postural stability remains to be investigated, particularly in older adults.

There has been limited information regarding asymmetric APA based on the hand used to perform the movements in young adults (Teyssèdre et al., 2000; Ypsilanti et al., 2009). In right-handed individuals, the dominant hand typically plays a more significant role in skillful, dynamic movement tasks (e.g. hammering or cutting) while the non-dominant hand mainly serves to stabilize posture (e.g. holding the object) (Sainburg, 2005). After life-long preferred use of the dominant hand, it is possible that APA become more proficient in estimating and counteracting the forthcoming perturbations associated with the arm movements. Consequently, increased postural instability will be present during movements made by the non-dominant compared to the dominant hand. However, the above assumption has not yet been examined.

In view of the limitations from previous studies, this dissertation was to investigate postural and arm movement control during standing reach in young and older adults. More specifically, the effects of the workspace and the functional goals of reaching movements on postural control were assessed. Further, whether there exits asymmetric postural control based on the dominant versus non-dominant arm was explored. Lastly, whether the constraints of maintaining standing balance and the need to incorporate the trunk in the reach can affect the formation of hand trajectories was examined. The results will further elucidate the impact of age-related changes in postural and movement control on the performance of reaching tasks during daily activities in older adults.

Dissertation Hypotheses

The first experiment examined age differences in APA and dynamic balance during movement execution (Chapter 2), and whether age affects hand trajectories and trunk movements (Chapter 3) during reaching to targets at different heights. In this experiment, all tasks were performed with the dominant and non-dominant arm.

In Chapter 2, the primary hypothesis was that older adults would show reduced APA amplitudes as measured by the COP displacement, and altered dynamic balance control during movement execution as reflected by the smoothness of COP trajectories.

In Chapter 3, the primary hypotheses were that for both young and older adults, the curvature of hand trajectories would be varied according to the target location in the workspace. In addition, older adults would exhibit straighter hand trajectories in order to minimize perturbations from reaching movements.

The second experiment was designed to investigate age differences in postural control during reaching when the movement context was altered by pointing to versus grasping the target (Chapter 4). The primary hypothesis was that in older adults, postural control measured by COP trajectory linearity would be affected by the movement context. The COP would show larger deviations from a straight path during grasping compared to pointing.

Chapter 2

Age Differences in Postural Control during Standing Reach

Introduction

Reaching tasks represent a significant component of activities of daily living (ADLs) and require control of both the arms and trunk, particularly when reaching is made from a standing position. Reaching movements can disturb postural stability due to the production of joint reaction torque and changes in body configuration. To counteract these forthcoming perturbations and maintain dynamic balance during movement execution, anticipatory postural adjustments (APAs) are generated prior to movement onset (Bouisset & Zattara, 1981, 1987; Leonard et al., 2009; Stapley et al., 1998; Zattara & Bouisset, 1988). The need to control disturbance to postural stability arising from moving multiple body segments can be challenging for older adults, where up to 95% of ADLs involve both arm and trunk movement (Clark et al., 1990). Despite the frequency of such motor tasks in everyday activities, our understanding of the factors impacting postural stability during reaching in older populations remains limited. For example, almost 20 percent of community-dwelling older adults report difficulties when reaching up above head level while over 50 percent have difficulties during downward directed movements, such as stooping or crouching (Ervin, 2006). Nevertheless, postural control during reaching movements performed from a standing position has been predominantly examined with individuals reaching horizontally at shoulder height (Bleuse et al., 2006; Duncan et al., 1992; Rogers et al., 1992; Woollacott & Manchester, 1993). More importantly, no studies have investigated APAs during reaching up and downward in older adults despite the everyday need to reach for objects located at different heights.

It has been well established that APAs are programmed in a feedforward mode with both APA duration and amplitude scaled to the estimated perturbation resulting from the forthcoming movement. APA duration and amplitude increase with increases in movement speed (Bouisset et al., 2001; Horak et al., 1984; Mochizuki et al., 2004) and magnitude (Kaminski & Simpkins, 2001; Tyler & Karst, 2004). In addition to modulation with respect to movement parameters, there is some evidence that APAs associated with movements of the dominant versus non-dominant hand are programmed differently. However, existing studies have yielded conflicting results. For example, Teyssedre et al., (2002) found that APA duration was longer when pointing movements were made with the dominant compared to the non-dominant hand. In contrast, Ypsilanti et al. (2009) recently reported shorter APA durations associated with reaching with the dominant versus the non-dominant hand. Moreover, postural sway during movement execution, as measured by the COP displacement in the medial-lateral direction, was larger under the non-dominant hand reach condition. Therefore, the nature of asymmetric postural control based on upper limbs asymmetries is not clear.

Numerous studies have documented that the generation of APAs is affected by age. Man'kovskii et al. (1980) found that, when producing single leg flexion movements from standing at maximum speed, APA duration was reduced and loss of balance increased in older adults. The authors suggested that with age, less time was available to stabilize posture before movement initiation, which in turn, contributed to impaired dynamic balance during the performance of a voluntary movement. Subsequent studies have confirmed the presence of age-related reductions in APA duration during other types of voluntary tasks, such as unilateral arm raising movements (Bleuse et al., 2006; Rogers et al., 1992; Woollacott & Manchester, 1993). However, others have shown that APA duration was prolonged in older adults in tasks requiring arm pulling or pushing (Inglis and Woollacott, 1988), suggesting that age differences in APA duration may be influenced by the mechanical demands of the task (Woollacott and Manchester, 1993). In contrast to studies focusing on the timing of APAs, to what extent aging affects the APA amplitude associated with voluntary movements has not been investigated. While age-related changes in APA duration are typically considered the cause of inadequate postural stabilization during movement execution (Inglin & Woollacott, 1988; Woollacott & Manchester, 1993), this view has only been confirmed during leg movements where both APAs and dynamic balance during movement execution were examined (Man'kovskii et al., 1980). In contrast, little is known regarding the effect of age-related changes in APA amplitude with relation to dynamic balance during reaching movements performed from a standing position.

It has been established that aging is associated with declines in dynamic balance control as reflected by a reduction in stability limits, i.e. the maximum range of COP displacement within the BOS during reaching or leaning maximally (Duncan et al., 1992; Holbein-Jenny et al., 2007; King et al., 1994; Kozak et al., 2003; Paizis et al., 2008). To what extent external factors such as the reach direction or location impacts dynamic balance control in older adults is not well understood. Row and Cavanagh (2007) showed that age-related reductions in the maximum COP displacement were larger during upward reaching compared to forward reaching, suggesting that age differences in dynamic balance vary depending on reach height

In many of the above studies examining postural control in older adults, individuals were required to hold the end reaching posture (Duncan et al., 1992; Holbein-Jenny et al., 2007; Kozak et al., 2003; Paizis et al., 2008; Row & Cavanagh, 2007). In everyday reaching activities, however, the task often is not simply to reach and hold in a particular direction but to grasp an object and then return to an upright position. Whether more dynamic tasks present a greater challenge to control postural stability for older adults remains unclear. More specifically, dynamic balance control when one shifts the COP away from the boundaries towards the center of the BOS (e.g. during returning to upright posture from a forward reach posture) has not been explored.

The above review indicates that our understanding of age-related changes in APAs and dynamic balance during movement execution is still limited. The present study investigated two factors related to postural control during reaching movements: the effects of reaching to targets at various heights in the workspace and reaching with the dominant versus non-dominant arm. Three phases of postural control were examined: the APA phase, dynamic balance during the reaching phase, and dynamic balance during the return to an upright posture phase. For the analysis of postural control, COP was chosen as the primary variable because it represents the net neuromuscular effort in controlling the COG (Winter, 1990). The secondary variable was axial torque, which contributes to the stabilization of the trunk posture and assists in shifting the arm to the target during reaching (Yamazaki et al., 2005). These measures have been used in previous studies of APAs (Bleuse et al., 2005, 2006; Crenna & Frigo, 1991; Yiou et al., 2007) and dynamic balance (Alexandrov et al., 2001; Duncan et al., 1992; Holbein-Jenny et al., 2007; Kozak et al., 2003; Paizis et al., 2008; Row & Cavanagh, 2007) during voluntary movements performed from a standing position.

The primary hypothesis was that older adults would show reduced APA amplitude as measured by smaller COP displacement and reduced dynamic balance as demonstrated by decreased COP trajectory smoothness. The secondary hypotheses were that age differences in postural control would be more pronounced at the high or low compared to medium height targets, and during the returning compared to the reaching movement phases. Moreover, movements made with the non-dominant hand would show reduced APA amplitudes as measured by smaller COP displacement and reduced dynamic balance as represented by decreased COP trajectory smoothness compared to movements made with the dominant hand.

Methods

Subjects

Fourteen young (age = 20.0 ± 1.5 yr; 2 male and 12 female) and 16 older (age = 73.5 ± 5.3 yr; 3 male and 13 female) volunteers participated in this experiment. Young subjects were students and staff at the University of Michigan. Older subjects were recruited by posting flyers at local senior centers and retirement communities, and from a volunteer data bank at the Institute of Gerontology at the University of Michigan.

All subjects were right-handed, ambulatory without the use of assistive devices, and lived in the community independently. Based on a short questionnaire (Appendix A), individuals with a history of diabetes, neurological or debilitating musculoskeletal disorders, or body mass index ≥ 30 were excluded. The experiment was approved by the Institutional Review Board at the University of Michigan. Consent forms were provided to each individual prior to the experiment.

After each subject's consent, further testing was conducted to rule out individuals who were not right-handed, or had sensory or visual impairments. Handedness was determined by scores greater than 40 for the right hand using the original Edinburgh Handedness Inventory (Oldfield, 1971) (Appendix B). The scores for young and older subjects were, on average, 81 (± 12.8) and 80 (± 20.2), respectively. Great toe position and vibration sense was examined bilaterally following the protocol developed by Richardson (2002). To test for position sense, the medial and lateral surfaces of the great toe distal to the metatarsophalangeal joint were grasped with the thumb and index finger and the distal phalange was passively displaced approximately 1 cm in either the flexion and extension direction. With their eyes closed, subjects were asked to correctly identify whether the great toe had been displaced in the upward direction (extension) or downward (flexion) direction. A total of 10 joint displacements were randomly administered for each great toe in approximately 1 min. A correct response was recorded when the subject perceived the movement and identified the direction correctly. Individuals who were able to correctly identify 8 out of 10 movements were included. To familiarize the subject with the vibration sensation testing procedure, a tuning fork was struck and then held against the clavicle until the subject could no longer feel the vibration. At that point, the subject verbally reported "gone". This procedure was repeated by placing the tuning fork proximal to the nailbed of the great toe. The time between the striking of the tuning fork and when the subject reported "gone" was recorded. Individuals who perceived the vibration for less than 8 s were excluded from the study. Binocular vision, with corrected lens if needed, was tested with subjects reading a sentence on a paper at a distance of 40 cm. Individuals who were able to read the sentence scored 20/50 or better. Subjects with vision below 20/50 were excluded from the study.

In addition to sensory testing, cognitive and balance assessments were also performed in older adults. Cognition was examined with the Mini-Cog test (Borson et al., 2000). Individuals with scores indicating impaired cognition were excluded from participating in the experiment. A series of balance tests were conducted using the protocols developed by Duncan et al. (1992) for the Functional Reach Test (Duncan et al., 1992), by Podsiadlo and Richardson (1991) for the Timed Up and Go Test, and by Bohannon et al. (1984) for the Single Leg Stance Test. Balance scores in older adults were required to be within normal limits to rule out individuals at risks of falls.

Exclusion criteria values were determined based on scores reported in previous studies: (Functional Reach: below 29 cm (Brauer et al., 2000), Timed Up and Go: greater than 12 s (Shumway-Cook et al., 2000), Single Leg Stance: less than 14 s (Bohannon et. al, 1984; Heitmann et al., 1989).

Experimental protocol

Subjects stood barefoot on a force platform (AccuSway, AMTI, Inc.) with their feet oriented forward and outward and the second metatarsal at 15 deg from the mid-sagittal plane. The midpoints of the heels were separated by a distance of 10% of body height. To ensure consistent foot positioning between trials, an outline of the feet was traced on a paper covering the force platform.

Figure 2.1 presents the schematic set-up for the experiment. The reach target was a cylinder (5 cm in diameter, 15 cm in height, and 300 g in weight), placed at 110% of arm's length away from the right lateral malleous and was aligned with the reaching shoulder in the para-sagittal plane. There were three target heights determined by the level of the base of target: at the top of the head (high), at the height of the shoulder joint (medium), and at the level of the knee joint (low). Subjects reached to the target with the dominant or non-dominant hand. Testing order of conditions was randomized across subjects.

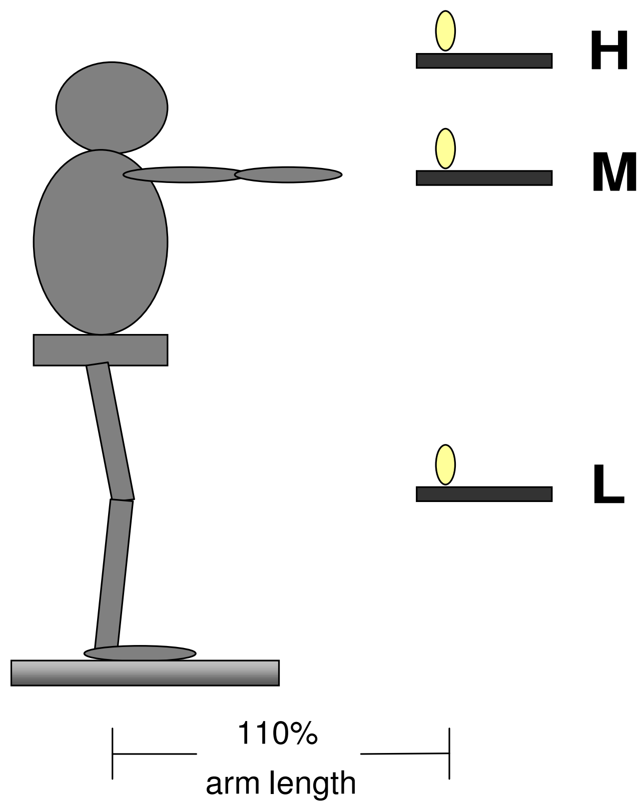

Figure 2.1 — Schematic representation of the experimental set up.
Target heights: H (high), M (medium), and L (low).

Prior to the beginning of each trial, subjects stood upright with their arms at 0 deg of shoulder flexion and abduction, 0 deg of elbow flexion and wrist flexion, forearm in semi-supination, thumbs pointing forward, and fingers fully extended. Upon hearing a "go" command, subjects initiated the movement at a self-chosen time. They were instructed to "reach, grasp the target, and return with the target in the hand to the upright posture as fast and accurately as possible". No specific instruction regarding movement strategies was given. Subjects were reminded to use a whole hand grasp to acquire the target and keep their feet in place during the task. Subjects performed 4 to 6 practice trials to become familiar with the task. Resting periods of 2 min were provided every 10 min during data collection to minimize fatigue. Three trials were performed for each condition for a total of 18 trials. Each trial lasted 8 s.

Data acquisition and analysis

Kinematics of bilateral wrist, shoulder, and hip movements were recorded using a three-dimensional motion capture system (Motion Star, Technology, Inc.). Sensors were placed at the wrist (midpoint between the radial and stylus processes over the dorsal surface), shoulder (lateral to acromioclavicular joint), and hip (greater trochanter) joint. Custom-written LabVIEW programs (National Instruments, Inc.) were used to calibrate the data recording system and collect kinematic data. Data were then processed and analyzed with costumed written Matlab programs (Matlab Version 6.0, The MathWorks, Inc.). All data were sampled at 100 Hz. A low-pass, fourth-order Butterworth digital filter at 6 Hz, 5 Hz, and 6 Hz was used for filtering data at the wrist, shoulder and hip joint, respectively. Filtering frequency was determined using the residual analysis of raw data (Winter, 1990). Movements of the hand were represented by data recorded from the wrist. Onset and offset of hand displacements was scored with a threshold equivalent to 5% of peak velocity.

Ground reaction forces and moments were recorded using a force plate at a sampling frequency of 100 Hz (AccuSway Plus, AMTI, Inc.). COP data were obtained from force plate software (Balance Clinic, AMTI, Inc.). Data were then processed and analyzed with costumed written Matlab programs (Matlab Version 6.0, The MathWorks, Inc.). These data were filtered with a low-pass, 4^{th} order Butterworth digital filter with a cutoff frequency at 6 Hz, which was determined by the residual analysis of unfiltered raw data (Winter, 1990). Axial torque (Tz) was calculated using the following equation (Bleuse et al., 2005):

$$Tz = Mz + COPy \times Fx - COPx \times Fy,$$

where Mz is the vertical component of the moment produced by the force platform; $COPx$ was the COP displacement in the anterior-posterior (AP); $COPy$ was the COP displacement in the medial-lateral (ML) direction; Fx is the AP component of the ground reaction force; Fy is the ML component of ground reaction force.

Onset and offset of the hand and COP displacements, and Tz were determined with a threshold equivalent to 5% of peak velocity or the first derivative of the data. Since the COP displacement primarily occurred in the AP direction, onset and offset of COP movements were determined with the COP displacement in the AP direction.

Primary dependent variables

(1) *APA amplitudes measured by COP displacement*: As shown in Figure 2.2, APA amplitudes were determined from COP-AP (differences in the COP-AP position from the onset of COP-AP displacement to the onset of arm movements).

(2) *COP trajectory smoothness during movement execution*: COP trajectory smoothness in the AP and ML directions was quantified using normalized integrated jerk scores (NIJ) (Teulings et al., 1997) during the reach and return movement phases. This variable is normalized to the movement amplitude and duration and is without units. Jerk scores have been used to describe hand trajectory smoothness during arm movements (Goble &

Brown, 2008; Ketcham et al., 2002; Rohrer et al., 2002) and COP trajectory smoothness during gait initiation (Hass et al., 2004, 2008). NIJ was calculated using the equation:

$$\text{NIJ} = \sqrt{(1/2 \times \int J^2(t)\, dt \times d^5 / l^2)},$$

where J is the third derivative of COP displacement, d is the movement duration of each phase analyzed, and l is the path length of COP during the corresponding phase. Values of normalized jerk were calculated separately for the reach movement phase (from the onset of hand movement to the time of maximum forward displacement of COP), and for the returning movement phase (from the time of maximum forward displacement of COP to the offset of backward displacement of COP) (Figure 2.2).

Secondary dependent variables

(1) APA amplitudes measured by Tz: Difference in Tz between the onset of Tz and the onset of arm movement corresponded to APA amplitude (Figure 2.2).

(2) *APA duration*: APA duration corresponded to the time from the onset of COP-AP displacement or Tz to the onset of arm movements (Figure 2.2).

(3) *COP maximum displacement*: COP maximum displacement was the difference in COP between the onset and the peak in the AP and ML directions (Figure 2.2).

(4) *Peak Tz:* Peak value of Tz during the reach and return movement phases was scored (Figure 2.2).

(5) *Postural sway:* COP path length in the AP and ML directions during a 2 s period following the offset of COP backward displacement corresponded to postural sway.

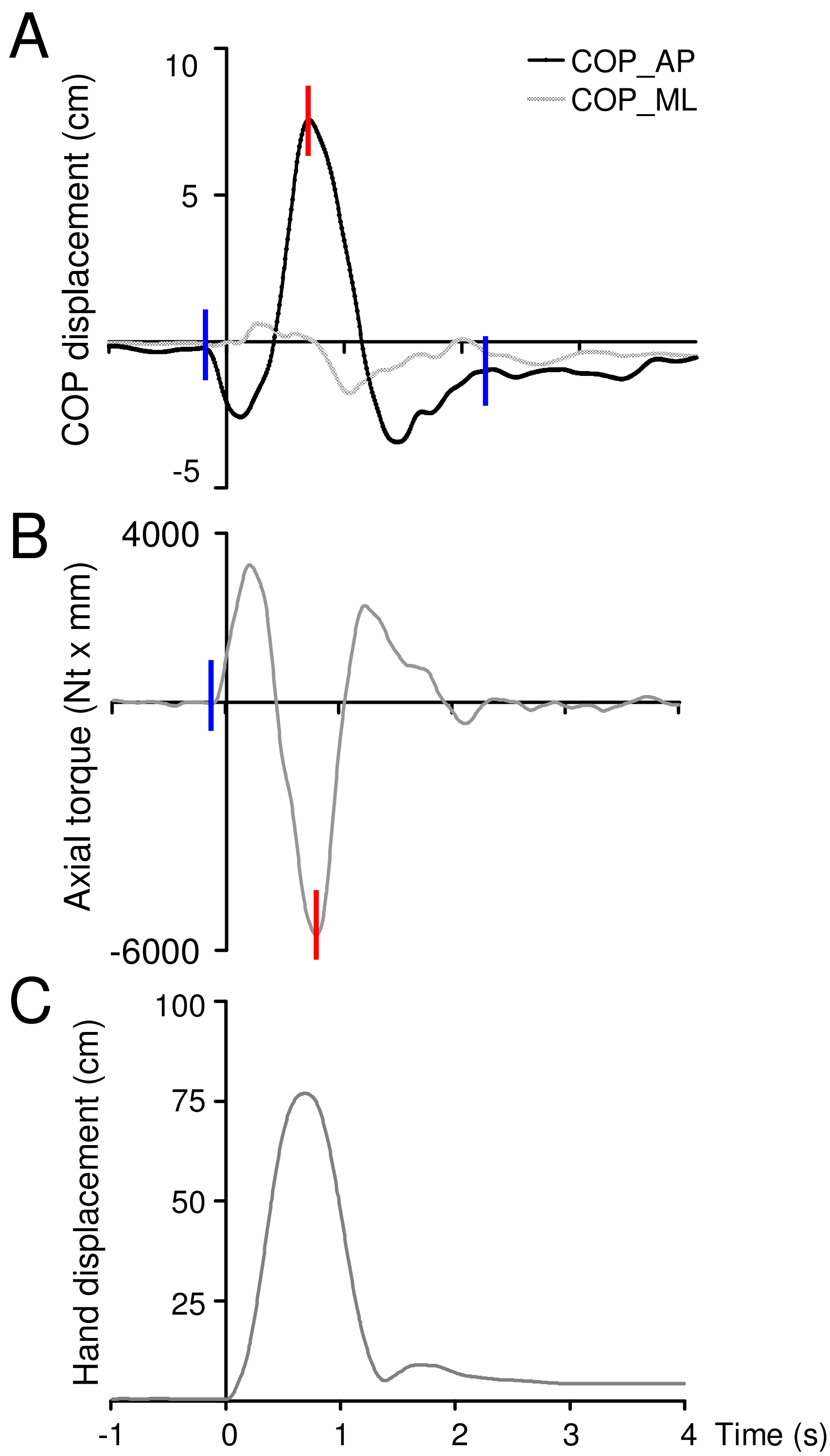

Figure 2.2 – COP displacement in the AP and ML directions (A), axial torque (B), and hand displacement in three dimensions (C) from one subject under dominant hand reach condition. Onset of hand displacement (Time = 0 s). Peaks of COP and Tz (|). Onset and offset of COP-AP and Tz (|).

(6) *Hand mean velocity:* The total hand displacement in three dimensions divided by the duration from the onset to the offset of hand reaching movements was hand mean velocity.

Statistical analysis

his experiment was a repeated measure design with age (young, older) as the between-subject factor, target height (high, medium, low) and hand used for performing the task (dominant hand, non-dominant hand) as the within-subjects factors. Means from all trials within each condition were submitted for statistical analysis with SPSS version 16. Post-hoc analysis was performed using Tukey's LSD method for the effects of age and hand, and adjusted using the Bonferroni method for the effect of target height. The effect size was evaluated with partial eta squared (η_p^2), which is a measure commonly used in experiments with repeated measure designs. Partial eta squared (η_p^2) assesses the relative contribution of each factor (independent variable) on the response variable (dependent variable) (Britz et al, 2009; Cohen, 1988; Mayer et al., 2006; Starr et al., 2004). Values of η_p^2 reported in previous studies with repeated measure designs are shown in Appendix C for reference. Independent t-tests were performed to compare the anthropometric parameters between young and older subjects. The level of statistical significance was set at $p<0.05$.

Results

Body size and height were comparable in both age groups as indicated by measures of height, weight, and arm length (Table 2.1). There were no significant group differences for any parameter.

Table 2.1 - Mean (± S.E.) anthropometry parameters of subjects.

	Body Height (cm)	Arm Length (cm)	Body Weight (Nt)
Young	167.2 ± 2.0	73.5 ± 0.9	609.1 ± 82.6
Older	166.2 ± 4.0	74.4 ± 1.6	664.9 ± 111.9

Hand mean velocity during reaching is shown in Table 2.2. Older adults had significantly slower mean velocities compared to young adults ($F_{1, 28} = 6.2$; $p<0.05$; $\eta_p^2 = 0.18$). Regardless of age, reaching to the high and the low targets was significantly associated with the largest and the slowest hand mean velocity, respectively. The effect of target heights was significant ($F_{1, 28} = 172.6$; $p<0.001$; $\eta_p^2 = 0.86$). For both groups, hand mean velocity was faster during reaching with the dominant compared to the non-dominant hand ($F_{1, 28} = 4.5$; $p<0.05$; $\eta_p^2 = 0.14$).

Table 2.2 - Mean (± S.E.) hand mean velocity (cm/s) during reaching.

	Young	Older
Dominant Hand		
High	158 (11)	133 (6)
Medium	146 (17)	128 (4)
Low	116 (14)	91 (4)
Non-Dominant Hand		
High	152 (8)	124 (5)
Medium	141 (7)	125 (5)
Low	109 (9)	88 (4)

Anticipatory postural adjustments

(1) Primary variable: APA amplitude measured by COP displacement

The COP was initially shifted in a backward direction prior to the onset of hand movement as shown in Figure 2.2A. Following the onset of COP displacement, COP maximum backward displacement occurred approximately at 326 ± 6 ms in young adults and 298 ± 5 ms in older adults across all target heights and hand conditions. As the hand began to move, COP was shifted forward towards the target.

APA amplitude was significantly greater in older than in young adults ($F_{1, 28}$ = 4.8; p<0.05; η_p^2 = 0.15) (Figure 2.3). For both groups, APA amplitude was significantly altered by target height ($F_{1, 28}$ = 96.1; p<0.001; η_p^2 = 0.77). Post-hoc comparisons revealed that reaching to the low target was associated with the largest APA amplitude compared to the other targets (Bonferroni method: p<0.05). Regardless of groups and heights, reaching with the dominant hand was associated with significantly larger APA amplitudes compared to the non-dominant hand ($F_{1,\,28} = 7.7$; $p<0.05$; $\eta_{part}^2 = 0.22$).

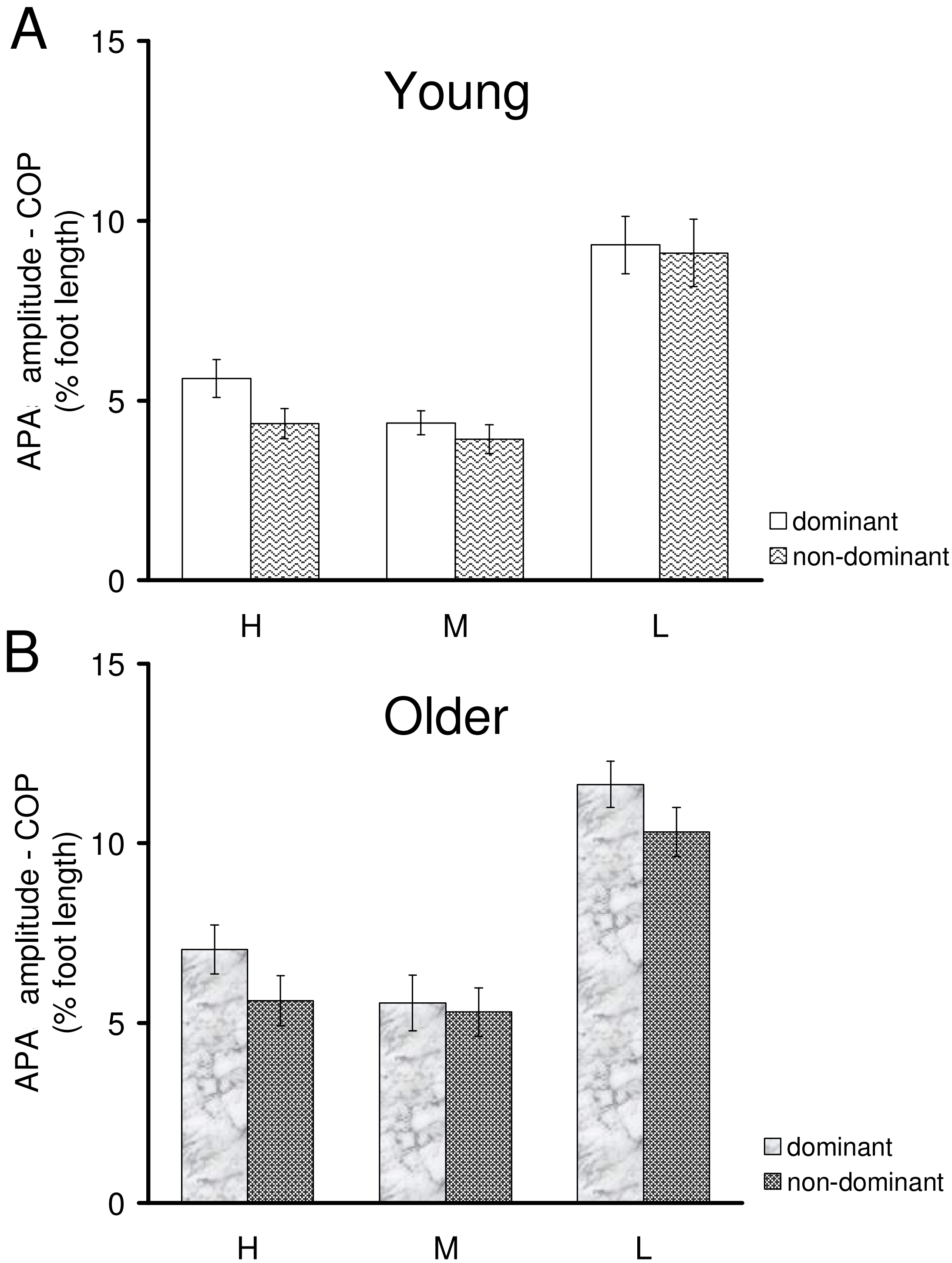

Figure 2.3 – Mean (± SE) APA amplitude (COP displacement) in young (A) and older adults (B). Group, *p*<0.05. Height, *p*<0.001. Hand, *p*<0.05.

(2) <u>Secondary variable: APA duration measured by COP</u>

As shown in Figure 2.4, APA duration was comparable between groups. For both young and older adults, APA duration was significantly influenced by target height ($F_{1, 28}$ = 87.2; p<0.001) while differences in APA duration between hands varied depending on target height (height by hand effect: $F_{1, 28}$ = 5.3; p<0.05). Post-hoc comparison revealed that reaching with the dominant hand was associated with significantly longer APA duration compared to with the non-dominant hand for high and low targets (LSD method: p<0.05; η_p^2 = 0.19 for high target; η_p^2 = 0.15 for low target). No differences between hands were found when reaching to medium height targets.

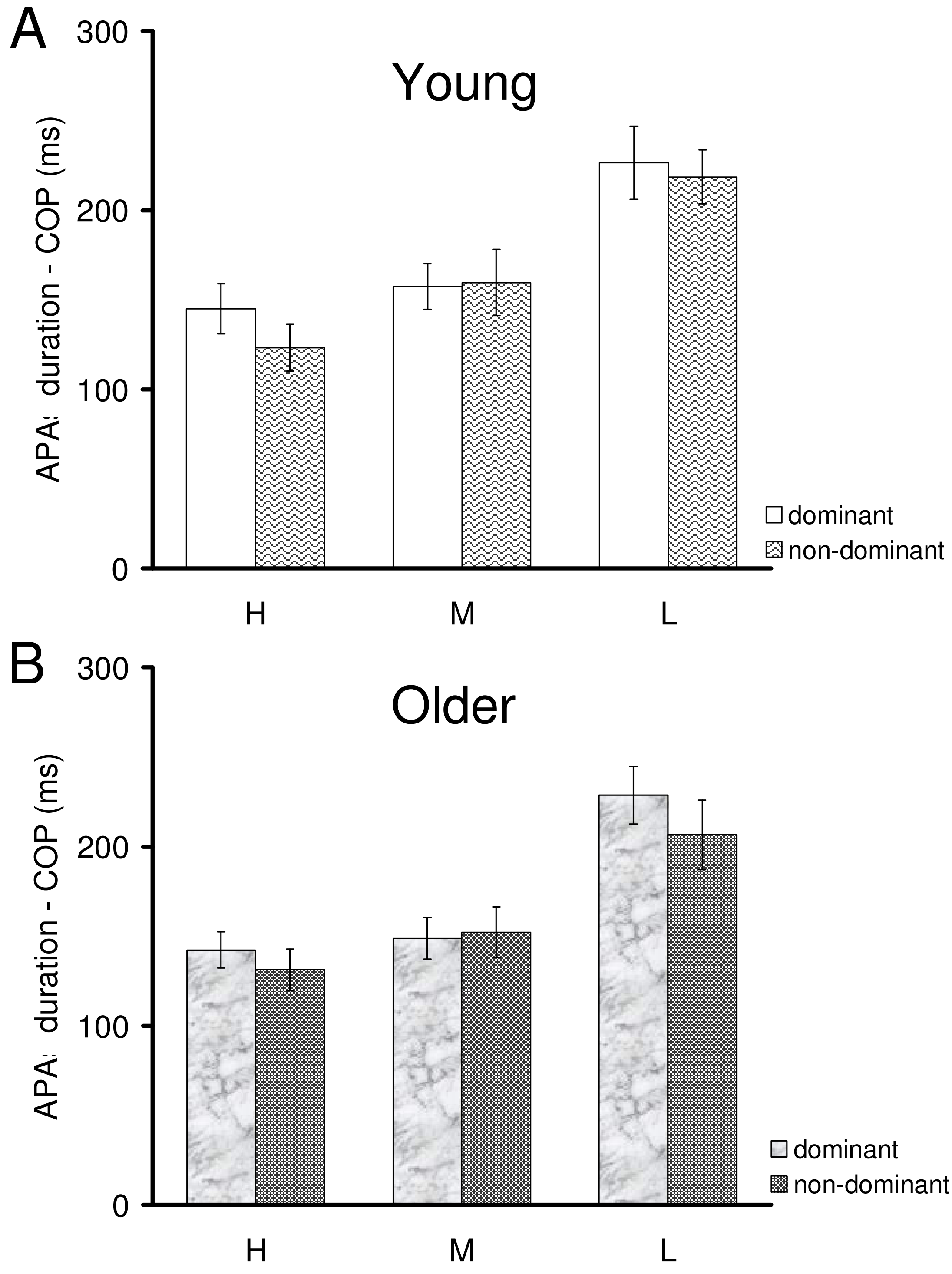

Figure 2.4 – Mean (± SE) APA duration (COP displacement) in young (A) and older adults (B). Height, $p<0.001$. Height by Hand, $p<0.05$.

(3) Secondary variable: APA amplitude measured by Tz

Axial torque (Tz) corresponds to the rotational effect of ground reaction forces acting on the whole body. As shown in Figure 2.2, prior to the onset of dominant hand reaching movement, Tz was positive, indicating that ground reaction forces act to rotate the whole body in a clockwise direction (CW) (viewed from above). Conversely, Tz was initially negative under the non-dominant hand reach condition, indicating that Tz rotated the whole body in a counter clockwise (CCW) direction.

Figure 2.5 displays APA amplitude measured by Tz. The effect of age was not significant. For both groups, APA amplitude was significantly greater for low than for higher targets ($F_{1, 28} = 50.3$; $p<0.001$; $\eta_p^2 = 0.64$). In older adults only, APA amplitude was different between hands (group by hand effect: $F_{1, 28} = 5.7$; $p<0.05$), with the dominant hand showing significantly greater APA amplitude than the non-dominant (Post hoc with LSD method: $p<0.01$; $\eta_p^2 = 0.25$).

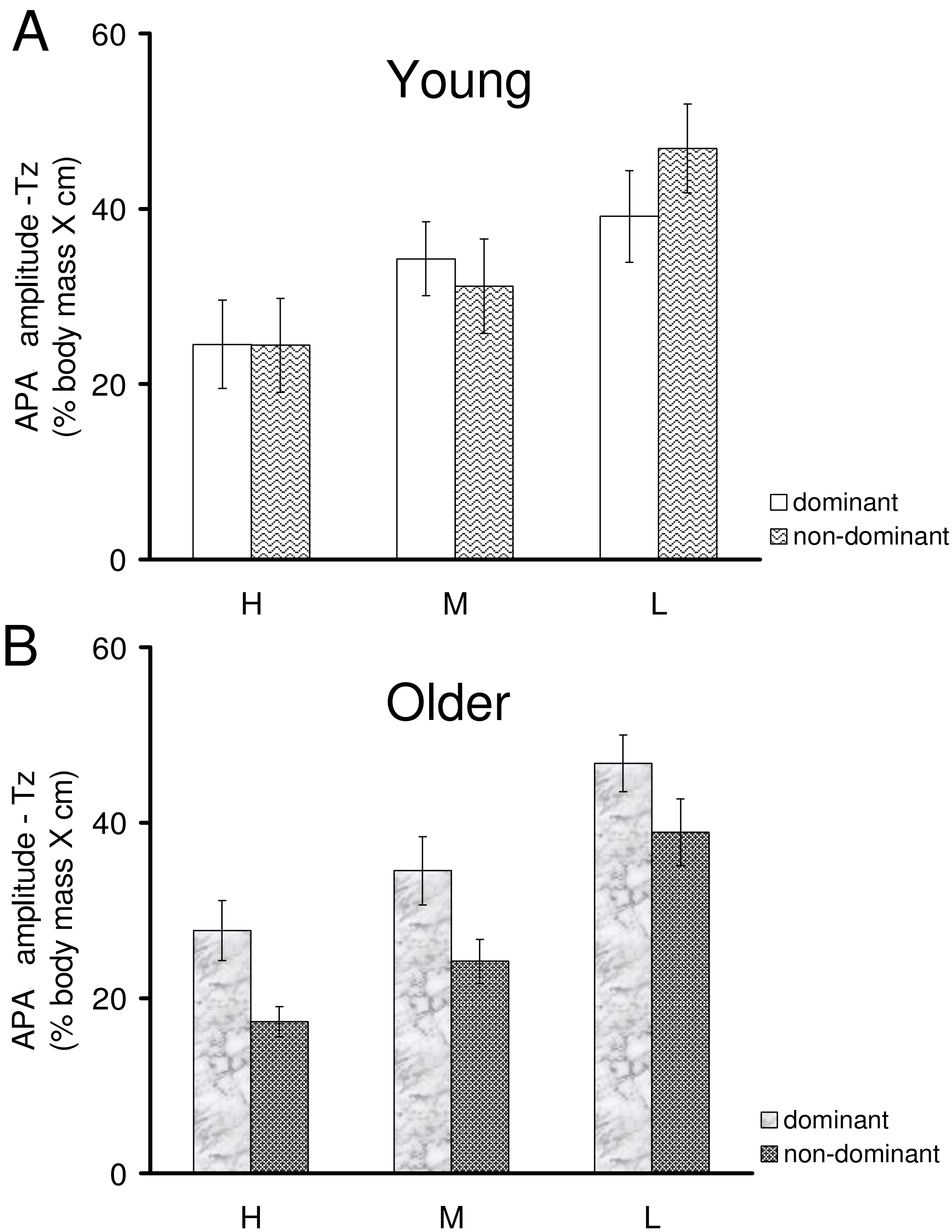

Figure 2.5 – Mean (± SE) APA amplitude (Tz) in young (A) and older adults (B). Height, $p<0.001$. Group by Hand, $p<0.05$.

(4) Secondary variable: APA duration measured by Tz

As shown in Figure 2.6, APA duration was comparable between groups. For both young and older adults, APA duration was significantly longer for low than for higher targets ($F_{1, 28} = 72.2$; $p < 0.001$; $\eta_p^2 = 0.65$). For both young and older adults, differences in APA duration between hands were significant only for high targets (hand by height effect: $F_{1, 28} = 9.8$; $p < 0.01$; $\eta_p^2 = 0.15$) (Post hoc with Bonferroni method: $p < 0.05$).

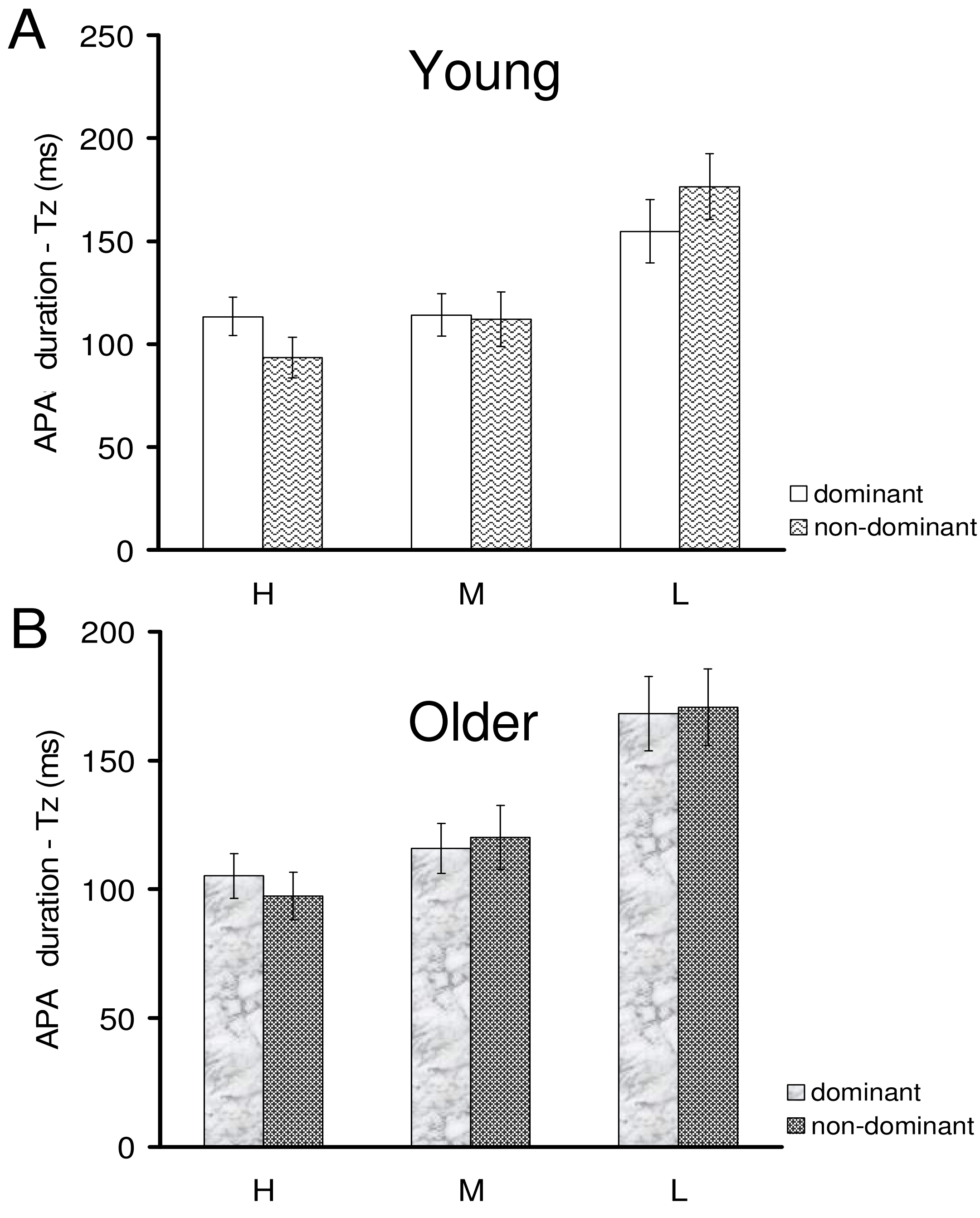

Figure 2.6 – Mean (± SE) APA duration (Tz) in young (A) and older adults (B). Height, *p*<0.001. Hand by Height, *p*<0.01.

Dynamic balance during movement execution

(1) Secondary variable: COP maximum displacement

During movement execution, maximum COP displacements in the forward (Figure 2.7 A) and medial-lateral (ML) directions (Figure 2.7 B) were comparable between groups. As shown in Figure 2.7, maximum COP forward displacement was the largest for high targets and the smallest for low targets ($F_{1, 28} = 145.4$; $p<0.001$; $\eta_p^2 = 0.90$), with significant differences between all levels of target heights (Post-hoc with Bonferroni method: $p<0.001$). Maximum COP ML displacement was the largest for low targets and the smallest for high targets ($F_{1, 28} = 36.0$; $p<0.001$; $\eta_p^2 = 0.56$), with significant differences between all levels of target heights (Post-hoc with Bonferroni method: $p<0.05$). No differences in maximum COP displacement were found between reaching with the dominant versus non-dominant hand in either the forward or ML directions.

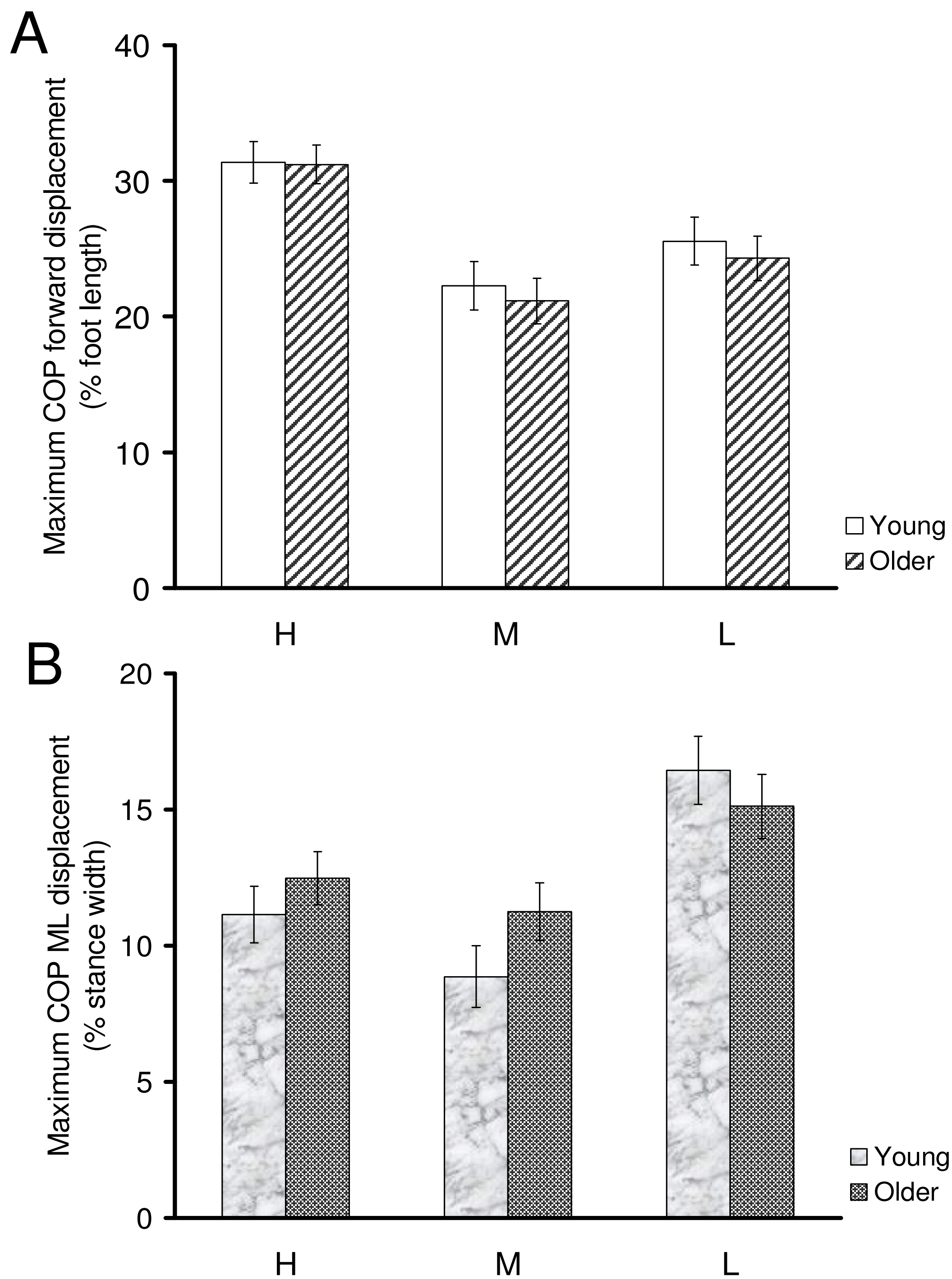

Figure 2.7 – Mean (± SE) COP maximum AP (A) and ML (B) displacements in young and older adults. Data collapsed across hand conditions. Height, p<0.001 for both COP maximum AP and ML displacements.

(2) Primary variable: COP trajectory smoothness during reaching

COP trajectory smoothness during the reaching movement phase is shown in Figure 2.8. For low targets, older adults had significantly greater normalized jerk scores, indicating a reduced COP trajectory smoothness (group by height effect: $F_{1, 28} = 16.6$; $p<0.001$; $\eta_p^2 = 0.37$; group effect: $F_{1, 28} = 8.6$; $p<0.01$; $\eta_p^2 = 0.23$; height effect: $F_{1, 28} = 93.7$; $p<0.001$; $\eta_p^2 = 0.77$) (Post hoc with LSD method: $p<0.05$). Moreover, smoothness of COP trajectory was reduced during reaching with the non-dominant hand compared to with the dominant hand ($F_{1, 28} = 4.3$; $p<0.05$; $\eta_p^2 = 0.17$).

(3) Primary variable: COP trajectory smoothness during returning

COP trajectory smoothness during the returning movement phase is shown in Figure 2.9. Across all target heights and hand conditions, older adults had a significant reduction in COP trajectory smoothness compared to young adults ($F_{1, 28} = 7.6$; $p<0.05$; $\eta_p^2 = 0.21$). Target height and dominant versus non-dominant reaching, however, had no significant effect on trajectory smoothness.

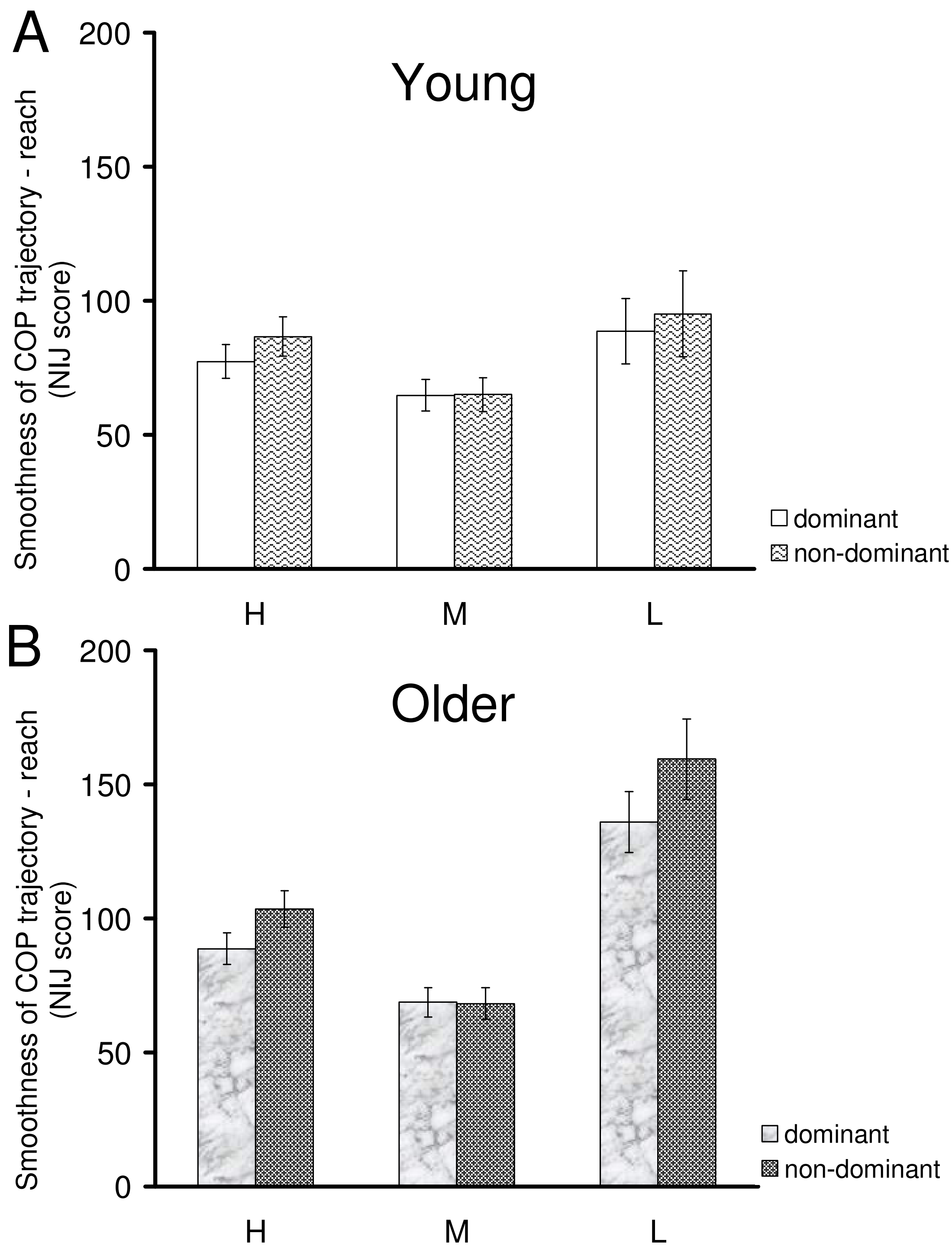

Figure 2.8 – Mean (± SE) COP trajectory smoothness measured by normalized jerk score (NIJ score) during reaching in young (A) and older (B) adults.

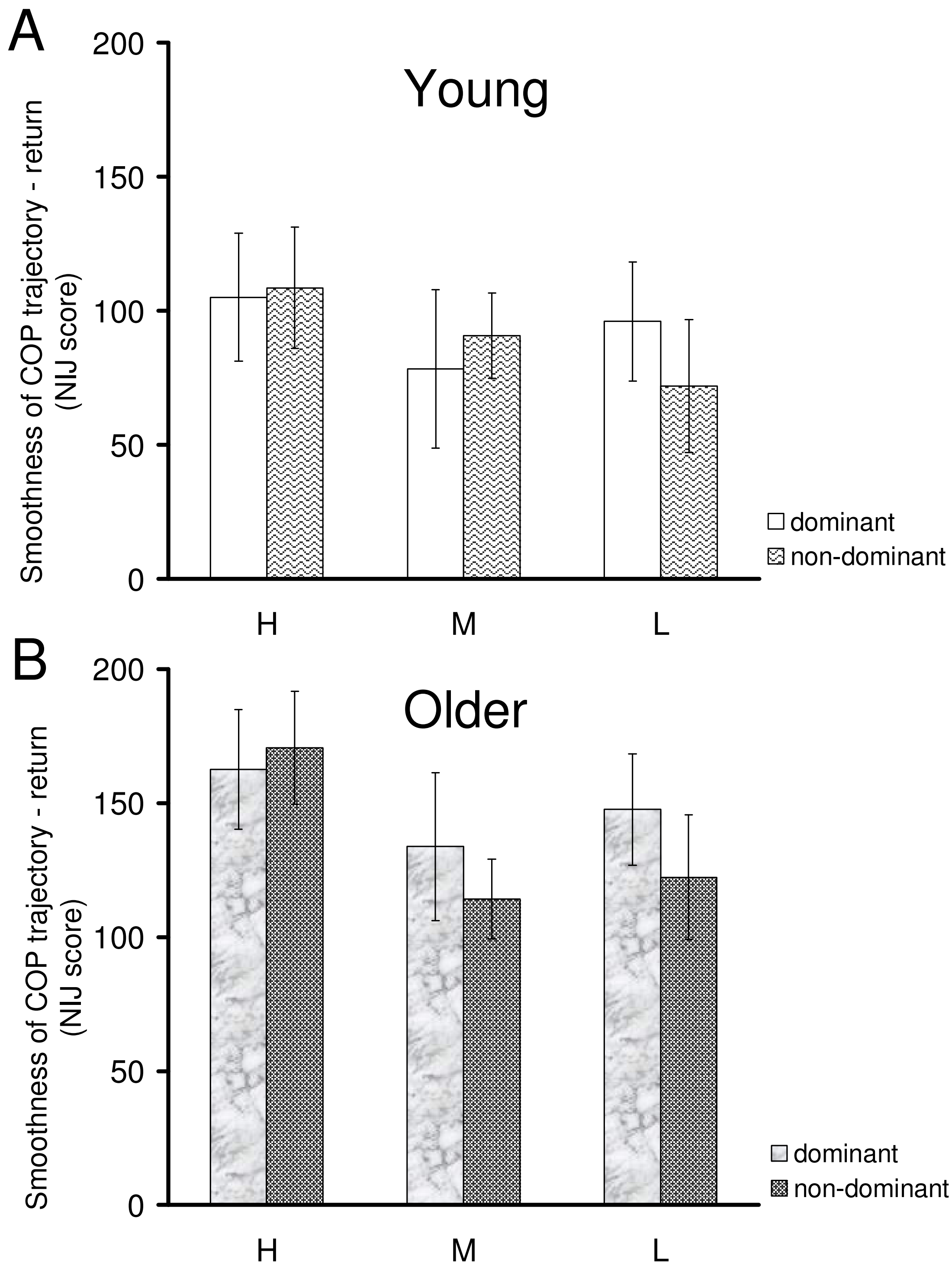

Figure 2.9 – Mean (± SE) COP trajectory smoothness measured by normalized jerk score (NIJ score) during returning movement in young (A) and older (B) adults.

(4) Secondary variable: peak Tz during the reaching and returning movement phases

As shown in Figure 2.10, for high and low targets, older adults showed a significant reduction in peak Tz (group by height effect: $F_{1, 28} = 6.6$; $p<0.05$; group effect: $F_{1, 28} = 6.2$; $p<0.05$; height effect: $F_{1, 28} = 36.8$; $p<0.001$) (Post hoc with LSD method: $p<0.05$). No differences associated with reaching with the dominant versus non-dominant arm were observed.

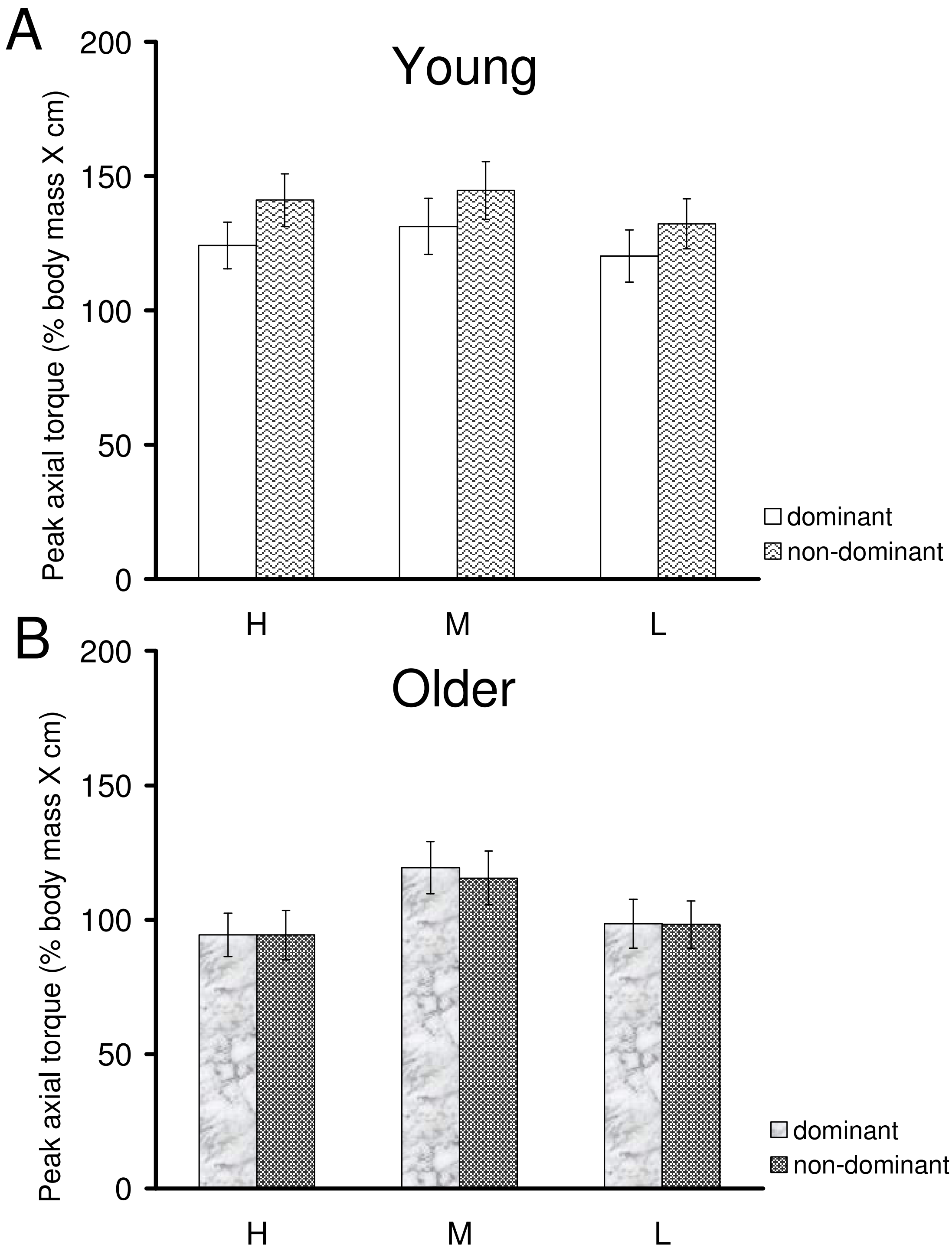

Figure 2.10 – Mean (± SE) Peak axial torque associated with target acquisition in young (A) and older (B) adults.

(5) Secondary variable: Postural sway after the end of movement

As shown in Figure 2.11, older adults had significantly longer COP path length, indicating increased postural sway with age after self-initiated movements ended ($F_{1, 28}$ = 15.5; p<0.001; η_p^2 = 0.36). For both young and older adults, COP path length was significantly greater for low targets than for higher targets ($F_{1, 28}$ = 75.2; p<0.001; η_p^2 = 0.73). Hand used for performing the task did not affect postural sway upon returning to upright posture.

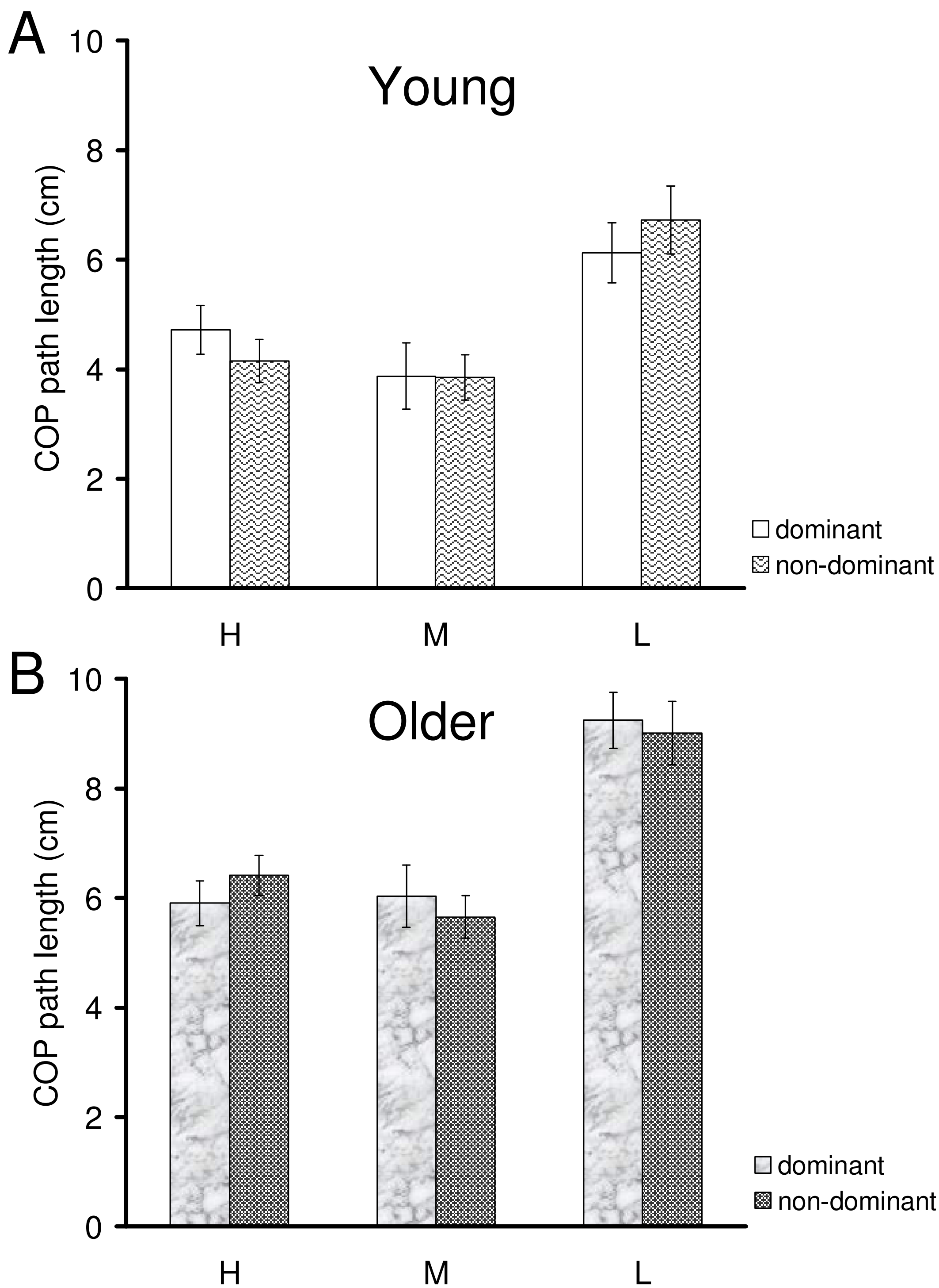

Figure 2.11 – Mean (± SE) COP path length in the anterior-posterior and medial-lateral directions after movement ended in young (A) and older (B) adults.

Discussion

Using the paradigm of standing reach to various heights with the dominant and non-dominant arm, this study examined age differences in APA production, dynamic balance during goal-directed reaching movements, and dynamic balance during the return to upright posture. This paradigm resembles many everyday activities which involve reaching to different heights in one's workspace with different arms. Further, this task did not require one to hold the end reaching posture at shoulder's height as is required in clinical measures of dynamic balance such as the Functional Reach test (Duncan et al., 1990, 1992).

Current results did not support the primary hypothesis based on previous findings of age-related reduction in APA duration associated with arm raising movements (Bleuse et al., 2006; Rogers et al., 1992; Woollacott & Manchester, 1993). Further, APA amplitude measured by COP displacement was larger in older adults while no differences in APA duration were found between groups, regardless of target heights. As hypothesized, dynamic balance as measured by COP trajectory smoothness was reduced in older adults during reaching to low targets and during returning to an upright posture from all target heights. In addition to the above main findings, the results confirmed the secondary hypothesis that the non-dominant hand condition was associated with a reduction in APA amplitude and COP trajectory smoothness during reaching.

Effects of age on APA amplitude: Primary hypothesis

The present study is the first to report an age-related increase in APA amplitude during standing reach, regardless of target heights in the workspace. APA amplitude is generally scaled with the magnitude of the reach distance (e.g. kinetic energy and work) during arm raising tasks (Bouisset et al., 2000). While reach distance was comparable across subjects (110% arm length), hand average velocity was actually slower in older adults. Therefore, age-related increases in APA amplitude were unlikely to counteract postural perturbations arising from faster or larger reaching movements for older adults.

Larger APAs with age may reflect an active “over-control” to increase the safety margin for preventing loss of balance. The state of postural stability is a result of the interaction between active control by muscles forces, passive effects from reaction forces, gravitational forces, and other external forces arising from the objects in the environment. Older adults might have generated larger APAs in order to minimize the disturbance from passive and external forces, which are less predictable and controllable. This anticipatory “over-control” may be viewed as an adaptive response used by older adults in order to reduce reliance on later, potentially inadequate compensatory postural responses and thus minimize postural instability.

Indeed, such an “over-control” strategy has also been observed during forward trunk bending movements, with older adults showing significantly larger tibialis anterior activity during the first 200 ms compared to younger adults (Vernazza-Martin et al., 2008). Similarly, following balance training with Tai Chi, older adults were found to reduce APA amplitude measured by postural muscle activity while dropping a load from a standing position (Forrest, 1997). It was concluded that practicing Tai Chi leads to a greater use of peripheral structure elasticity (e.g. muscles, ligaments, and tendons) for maintaining balance while the contribution from central postural control mechanisms is decreased. In light of the above findings, current results indicate that, in addition to using an over-control anticipatory strategy, older adults may have been unable to exploit the passive mechanical effects for feedforward postural control to the same extent as young adults, thus leading to increased APA amplitude.

Effects of age on APA duration

Studies of unilateral arm raising movements have shown that APA duration measured by the COP and Tz reduced with age (Bleuse et al., 2006). In the present study, APA duration measured by COP and Tz was comparable between groups. It has been suggested that age differences in APA duration vary depending on the magnitude of movement disturbance (Woollacott & Manchester, 1993). When the arm movement requires the generation of forces involved in, for example, pushing or pulling a handle, older adults produce longer duration APAs (Inglin & Woollacott, 1988). In contrast, in tasks where the arm points upward, APA duration decreases with age (Bleuse et al., 2006; Rogers et al., 1992; Woollacott & Manchester, 1993). In current reaching tasks, forward trunk movements also contributed to bringing the hand to the target. Since the disturbance generated by moving the trunk is larger than simply raising the arm upward, it is unlikely that older adults in the present study would produce shorter APA durations. The observation that APA durations were comparable between age groups indicates that older adults were able to generate APA in a timely manner in these types of reaching tasks.

Effect of age on dynamic balance: Primary hypothesis

During movement execution, maximum COP displacement was comparable between young and older groups. In contrast, COP trajectory smoothness was significantly reduced in older but not young adults. To date, dynamic balance has mostly been examined using maximum COP displacement (Duncan et al., 1992; Holbein-Jenny et al., 2007; King et al., 1994; Kozak et al., 2003; Paizis et al., 2008; Row & Cavanagh, 2007). In contrast, the spatial-temporal characteristics of COP trajectories have been mostly examined in quiet stance (Lin et al., 2008; Rougier, 2008) rather than during movement execution. There has been some evidence suggesting that COP trajectory smoothness reflects changes in balance function in older adults. For instance, COP trajectory smoothness during gait initiation was found to improve in older adults following balance training programs although an age comparison of trajectory smoothness prior to training was not performed (Hass et al., 2004). Moreover, elderly patients with Parkinson's disease show decreased COP trajectory smoothness during gait initiation compared to healthy older adults (Hass et al., 2008). In this connection, current findings of age-related reductions in COP trajectory smoothness may be a more significant indicator of altered dynamic balance control compared to the measure of maximum COP displacement.

Age-related declines in COP trajectory smoothness was also evident during reaching to low targets. Under this condition, the reach was extended using trunk movement and consequently was more challenging for postural control due to moving the large mass of the trunk. During returning to an upright posture, COP trajectory smoothness was reduced in older adults under all target height conditions. Thus, shifting the COP smoothly in the backward direction may be more difficult for older adults, regardless of the amount of trunk movement involved in the task as varied by different target heights. In fact, shifting the COP forward may be easier because the distance from the ankle joint to the boundaries of the BOS is longer in the anterior compared to the posterior directions. This allows for a longer lever arm for generating forward movements.

Lastly, reaching forward to a target is typically under visual guidance where the target or object of interest serves as a visual anchor to help control the reaching movement. Older adults show a greater range of COP displacement and faster COP speeds when a stable visual anchor is changed (Simoneau et al., 1999). Likewise, in current reaching tasks, a previously stable visual anchor, i.e. the target, was no longer available after subjects grasped and returned with it to an upright position. Thus, in older adults, removal of this visual anchor could have had a greater impact on dynamic balance during the return phase.

Effects of target height on APA and dynamic balance: Secondary hypothesis

In the present study, APA amplitude measured by the COP displacement and Tz were significantly larger at low compared to other higher targets for both young and older adults. Since APA amplitude is modulated according to the predicted magnitude of movement disturbance (Bouisset et al., 2000; Horak et al., 1984; Shiratori & Aruin, 2007), current findings imply that the demands for stabilizing posture may be the greatest under the low target condition.

During movement execution, maximum COP displacement in the forward direction was the largest during reaching to high targets whereas COP displacement in the medial-lateral direction was the largest during reaching to low targets. Unlike reaching in the forward and upward directions, reaching downward to low targets involved a backward hip movement, which may have canceled out some forward COP displacement (Alexandrov et al., 1998). Larger COP displacements in the medial-lateral direction under the low target condition indicate a greater challenge in controlling postural stability in the frontal plane.

Effects of hand on APA and dynamic balance: Secondary hypothesis

Previous research has provided conflicting evidence regarding APAs associated with movements made by the dominant versus the non-dominant hands in young adults. For the dominant hand movement, APA duration was found to be longer in studies examining seated subjects (Teyssedre et al., 2000) but shorter in studies examining standing subjects (Ypsilanti et al., 2009). The present study is the first to report that, for both young and older adults, APA amplitudes and durations measured by COP are greater during standing reach with the dominant compared to the non-dominant hand. This hand effect was more pronounced during reaching to low and high targets, which required a larger trunk displacement and, thus, a higher degree of multi-joint coordination and postural stabilization compared to reaching forward to medium height targets. As suggested by the dynamic dominance hypothesis, the dominant hand system is superior in feedforward control of intersegemental reaction torques (Bagesteiro & Sainburg, 2002; Sainburg, 2002; Sainburg & Kalakanis, 2000; Wang & Sainburg, 2005). Thus, it is possible that feedforward postural control associated with the dominant hand movement is also more proficient in stabilizing posture, which can be reflected by an increase in COP trajectory smoothness during reaching with the dominant hand.

APA amplitude measured by the axial torque (Tz) was significantly different between hands but only in older adults. Anticipatory Tz functions to stabilize the trunk and consequently assists in the execution of arm movements made towards the target (Bleuse et al., 2006; Yamazaki et al., 2005). There is evidence supporting the theory that anticipatory postural muscle activity is organized asymmetrically with regard to the rotational perturbations arising from unilateral arm movements performed from a standing position. Thoracic multifidus and longissimus muscles are differentially activated with the rotational forces on the trunk depending on the arm used (dominant versus non-dominant) to execute the movements (Lee et al., 2009). Current results indicate that APAs related to trunk control and the generation of arm movements may become increasingly asymmetric after lifelong preferred use of the dominant hand. Indeed, according to Massion (1992, 1999), APAs are largely learned based on previous experience with a movement disturbance. Preferential use of the dominant hand over an extended period of time can lead to the formation of a more elaborate internal model, which encodes the body orientation and dynamics for postural control. As a result, the dominant hand / feedforward postural control system may become more resistant to age-related declines in motor and postural control.

Implications

This dissertation demonstrates that older adults produce larger APAs, a strategy to increase the safety margin for preventing loss of balance, and also show a reduction in COP trajectory smoothness during movement execution. To enhance postural control associated with movements, postural tasks in balance training programs should introduce sufficient repetitions of various types of movement disturbances (e.g. reaching to various heights and in different directions) and emphasize a controlled postural transition between movements to improve stability (e.g. increasing COP trajectory smoothness).

Older adults face greater challenges in postural control while performing movements directed in the backward compared to the forward directions. Clinical tests and training programs for balance should also include postural tasks involving backward-oriented movements. For instance, the Functional Reach test (Duncan et al., 1990) should be modified to include the movement phase of returning to upright posture. Furthermore, the assessment of postural control should incorporate movements made to different heights in the workspace, particularly the lower height. Tasks of simply raising the arm (Horak et al., 2009) or reaching maximally (Duncan et al., 1990) to the shoulder's height may not be the most sensitive tests in differentiating age differences in feedforward postural control. Lastly, to prevent further functional declines in the non-dominant hand / feedforward postural control system with age, practicing postural tasks involving reaching with the non-dominant arm movements should not be overlooked.

Limitations

The small sample size in the present study may be considered a limitation that precludes generalization of current findings. In the present study, repeated measures design permitted each subject to serve as his/her own control and reduced the variability associated with individual differences. This approach allows for more economical and powerful analysis despite smaller than usual subject groups (Fitzmaurice et al., 2009). Moreover, practice effects of the task over repeated trials were minimized because the order of conditions was randomized across subjects. Nevertheless, a larger group of older subjects, including more frail individuals, will further expand current findings to the general elderly population.

In both young and older groups, there was a small proportion (less than 20% total) of male subjects. Therefore, it was not feasible to analyze the effect of gender. Studies have reported gender-related differences in postural responses (Era et al., 2006; DeGoede & Ashton-Miller, 2003; Pavol et al., 1999; Wojcik et al., 1999, 2001). Wojcik et al. (2001) reported that during a forward fall, older women generated larger ankle plantarflexion torque compared to older men and younger men and women. Moreover, older women were the least able to recover balance with a single step compared to other groups (older men, younger men, and young women) (Wojcik et al., 1999). Pavol et al. (1999) reported that older women were four times more likely to fall than older men during trip-induced falls during gait although their observation was descriptive in nature and not based on statistical analysis. Thus it is possible that greater age differences would have been seen had only women been included for study. Based on the literature, however, studies of postural control associated with voluntary movements performed from a standing position, do not typically control for the effects of gender. Indeed, using the PubMed.gov search engine, 2 out of a total of 9 articles published in 2009 included only males, four studies recruited both men and women, while the other studies did not report the gender composition in their experiments.

The present study has other limitations, including instruction set, postural responses relative to one's maximum capacity, nature of a speeded task, within-subject variability in performance, and potential bias of data processing and analysis. These issues will be addressed in the section of general discussion (Chapter 5).

Future Studies

Further studies are necessary to reveal whether older adults are able to reduce APA amplitude with balance training and what are the intrinsic physiological (e.g. cognitive, sensorimotor, or musculoskeletal function) and extrinsic factors (e.g. structure and types of feedback, practice schedule, instructional set) impact the learning processes. Moreover, whether these changes in APA amplitude will be associated with improved postural stability during movement execution needs to be investigated. Findings from these analyses will provide insight into the formation of the internal model for feedforward postural control processes in older adults. Studies with a larger sample size of subjects include male and female subjects will be needed to reveal the potential influence of gender on APA production which has not been examined.

The present study demonstrates that the measure of COP trajectory smoothness may provide valuable information regarding dynamic balance, similar to postural sway measures with COP trajectory in quiet stance (Rougier, 2008). More research is needed to identify the processes affecting COP trajectory smoothness. For example, regression analysis of clinical measures of sensorimotor, cognitive, musculoskeletal, and functional balance with COP trajectory smoothness can be conducted to identify factors contributing to declines in the control of COP trajectory. By comparing COP trajectory smoothness between subjects of different diseases or risks of falls, different cutoffs can be determined to identify individuals with impaired postural control.

Conclusions

- Community dwelling older adults are able to modulate APA while performing reaching movements to various heights. However, older adults accomplish this by producing larger amplitude APAs as measured by COP displacement.
- Dynamic balance during movement execution is altered with age. Older adults show reduced smoothness of COP trajectory, particularly when the COP shifts in the backward direction.
- APA is organized asymmetrically based on dominant versus non-dominant arm movements. This asymmetry becomes more evident with age.

Chapter 3

Kinematics of Arm and Trunk Movements during Standing Reach in Young and Older Adults

Introduction

Reaching is one of the most important functional tasks during daily activities. When the reach distance is beyond arm's length, the trunk contributes to bringing the hand to the target. Due to the redundant degrees of freedom in the body, there are many possible combinations of joints angles to accomplish the same reach task (Bernstein, 1967). Nevertheless, studies of multi-joint arm movements have documented that hand trajectories approximate a straight line from the start to end point (Morasso, 1981; Soechting & Lacquaniti, 1981). Roughly straight hand trajectories are consistently observed regardless of the distance, velocity, and direction of arm movements (Georgopoulos et al., 1981; Morasso, 1981; Soechting & Lacquaniti, 1981) and whether or not the trunk participates in the reach (Kaminski et al., 1995; Ma & Feldman, 1995; Saling et al., 1996).

During reaching, movements of the trunk, a large of mass, can disturb hand trajectories. This disturbance is minimized by feedforward control (Bortolami et al., 2008; Pigeon et al., 2003a) with a synergy that coordinates the trunk and arm segments (Ma & Feldman, 1995). Moreover, the execution of reaching movements causes postural perturbations due to reaction joint torques and changes in the body configuration. Therefore, anticipatory postural adjustments (APAs) are needed to stabilize posture in advance (Massion, 1992). These postural mechanisms allow the CNS to consistently produce approximately straight hand trajectories despite the need to coordinate multiple body segments and maintain postural stability.

Studies have documented variations in the straightness of hand trajectories to elucidate processes underlying motor control. Hand trajectories have a small but gentle curvature depending on the regions in the workspace and movement direction (Atkeson & Hollerbach, 1985; Biess et al., 2007; Cruz & Kamper, 2006; Flash, 1987; Haggard & Richardson, 1996). For sagittal plane movements, hand trajectories are straighter when the arm moves forward in an anterior-posterior than a vertical direction (Atkeson & Hollerbach, 1985; Haggard et al., 1995) with increased curvatures during vertically oriented movements thought to be due to the influence of gravity (Atkeson and Hollerbach, 1985). More recently, Papaxanthis et al. (2003) reported that for movements made in the vertical plane, hand trajectories were straighter when the arm moved downward than upward, indicating that the CNS uses different planning processes depending on whether the gravitational field that acts along and against movement. Differences in the straightness of hand trajectories can also be task-specific. Desmurget et al (1997) showed that unconstrained (arm without contact with a surface) movements generally have larger curvature than constrained movements (arm supported and in contact with a horizontal surface). The results imply that the curvature of hand trajectories is a preplanned feature, reflecting the influence of task constraints on the programming of the movements.

In healthy young adults, the straightness of hand trajectories during reaching is not affected by the demands associated with maintaining standing balance. This was recently demonstrated by Berret et al. (2009) who explored the interaction between the constraints of postural stability and the constraints related to the shape of hand trajectories during whole body reaching to targets placed on the ground. Postural stability constraints were varied by asking standing subjects to reach from a normal or reduced base of support (BOS), and with knees maintained in the extended position. To change the constraints for hand trajectories, they instructed subjects to move the hand along a straight versus curved path while standing on a normal BOS. The results showed that the curvature of hand trajectories was similar regardless of the difficulty level for maintaining balance. In contrast, the COM displacement was increased when subjects were asked to make a curved compared to a straight path. They interpreted these results as providing further proof that straight hand trajectories are invariant characteristics controlled by the CNS and are independent of the constraints of postural stability. Since curved hand trajectories were associated with greater COM displacement, it was also concluded that curved hand trajectories would possibly lead to postural instability.

It has been well established that aging is associated with declines in postural control (Horak, 2006; Maki & McIlroy, 2006). During arm raising movements performed from a standing position, anticipatory postural adjustments (APAs) are less consistently present, with shorter duration, and display altered postural muscle recruitment patterns with age (Bleuse et al., 2005; Woollacott & Manchester, 1993). However, to what extent the constraints for maintaining postural stability affect the performance of reaching movements in older adults has received little attention. Since APAs are programmed specifically in response to the expected disturbance due to the upcoming movements (Aruin & Latash, 1995; Kaminski & Simpkins, 2001; Leonard et al., 2009), it is possible that reaching movements performed by older adults from a standing position may be affected by the demand to maintain postural stability. In a study examining hand trajectories during reaching to targets placed on the ground in standing young and older adults, Paizis et al (2008) recently showed that trajectories were actually straighter while maximum COP and COM displacements were smaller in older compared to young adults. The authors suggested that older adults may have limited COM displacement during movement execution by producing straighter reach trajectories. However, the experimental task used by Paizi et al required subjects to bend over during reaching and thus it is possible that the reported age differences in hand trajectories were related, at least, in part, to the amount of trunk movement employed by older adults.

In right handed subjects, the central processes for planning hand trajectories (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000) and coordinating arm and trunk movements (Esparza et al., 2003) are organized differently for the dominant and the non-dominant hemispheres. Sainburg and Kalakanis (2000) reported that when seated subjects performed reaching tasks to various targets on a horizontal surface, movement speeds and endpoint accuracy were similar between hands. However, the curvature of hand trajectories changed across targets during reaching with the non-dominant but not dominant hand. Moreover, for the non-dominant arm only, the curvature of hand trajectories was significantly correlated with the reaction joint torque during movement execution. Thus, the dominant hemisphere is more proficient in the formation of straight hand trajectories, possibly due to superior control of intersegmental reaction torques (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000).

Whether asymmetric central mechanisms for planning hand trajectories and arm-trunk coordination is affected by age has not been investigated. There has been evidence suggesting that after a life long preferred use of the dominant arm, manual asymmetry increases with age (Kilbreath & Heard, 2005). However, the expression of this asymmetry appears to be task dependent. Aging is associated with larger declines in motor performance of the non-dominant than dominant hand in tasks with higher demands of precision, attention, and visual tracking (Francis & Spirduso, 2000; Mitrushina et al.; 1995), such as sequential drawing (Teixeira, 2008), aiming and line tracing (Francis & Spirduso, 2000; Kalisch et al., 2006), and Purdue Pegboard tasks (Francis & Spirduso, 2000; Weller & Latimer-Sayer, 1985). In the above studies, age related changes in manual asymmetry were examined in tasks using only the arms only and from a seated position. It is not known whether this asymmetry extends to movements involving more proximal segments, such as the trunk, and with the demands to maintain standing balance.

With age, arm movements are typically slower (Bellgrove et al., 1998; Welford, 1984) with more variable hand trajectories (Darling et al., 1989; Ketcham et al., 2002). To date, most studies of age differences in arm movements have been conducted from a seated position with the arm moving on a horizontal plane (Bellgrove et al., 1998; Darling et al., 1989; Goggin & Meeuwsen, 1992; Ketcham et al., 2002; Welford, 1984). This type of experimental paradigm requires lower demands for coordinating the trunk and arm segments, and for maintaining postural stability. However, reaching tasks are commonly performed with movements of the trunk and from a standing position to various locations in the three-dimensional workspace. This raises the question whether reaching movements performed by older adults are affected by the demands to incorporate the trunk movement and to control postural stability. The present study investigated age differences in the kinematics of arm and trunk movements during standing reach to targets placed at different heights. Reaching to different vertical locations altered the amount of trunk displacement required to accomplish the task. In addition, subjects performed the task with the dominant and non-dominant hand. To determine how the CNS plans reaching movements performed from a standing position, the straightness of hand trajectories was chosen as the primary variable. The hand movement time was analyzed as a secondary variable to reflect the overall movement performance pertaining to the task goal of reach. Trunk flexion was also analyzed as a secondary variable in order to examine the role played by the trunk in standing reach.

Two primary hypotheses were tested. The first primary hypothesis was that hand trajectories would be straighter in older than young adults, regardless of the target heights and hand conditions. Older adults would make straight hand trajectories to minimize COM displacement and consequently, postural perturbations. The second primary hypothesis was that, for both young and older adults, the straightness of hand trajectories would vary depending on the target heights.

The secondary hypotheses were that older adults would show longer and more asymmetric movement times when reaching with the dominant versus the non-dominant arm, suggesting increased asymmetry in upper limb motor performance with age, and that older adults would reduce the amount of trunk movement produced during reaching, reflecting a strategy to minimize the disturbance from moving a large mass on hand trajectories.

Methods

Subjects

The same groups of young and older subjects as in Chapter 2 were analyzed in the present study. Fourteen young (age = 20.0 ± 1.5 year; 2 male and 12 female) and 16 older (age = 73.5 ± 5.3 year; 3 male and 13 female) volunteers participated in this experiment. Young subjects were students and staff at the University of Michigan. Older subjects were recruited by posting flyers at local senior centers and retirement communities, and from a volunteer data bank at the Institute of Gerontology at the University of Michigan. All subjects were right-handed, ambulatory without the use of assistive devices, and lived in the community independently. Based on a short questionnaire (Appendix A), individuals with a history of diabetes, neurological or debilitating musculoskeletal disorders, or body mass index ≥ 30 were excluded. The experiment was approved by the Institutional Review Board at the University of Michigan. Consent forms were provided to each individual prior to the experiment.

After each subject's consent, further testing was conducted to rule out individuals who were not right-handed, or had sensory or visual impairments. Handedness was determined by scores greater than 40 for the right hand using the original Edinburgh Handedness Inventory (Oldfield, 1971) (Appendix B). The scores for young and older subjects were, on average, 81 (± 12.8) and 80 (± 20.2), respectively. Great toe position and vibration sense was examined bilaterally following the protocol developed by Richardson (2002). To test for position sense, the medial and lateral surfaces of the great toe distal to the metatarsophalangeal joint were grasped with the thumb and index finger and the distal phalange was passively displaced approximately 1 cm in either the flexion and extension direction. With their eyes closed, subjects were asked to correctly identify whether the great toe had been displaced in the upward direction (extension) or downward (flexion) direction. A total of 10 joint displacements were randomly administered for each great toe in approximately 1 min. A correct response was recorded when the subject perceived the movement and identified the direction correctly. Individuals who were able to correctly identify 8 out of 10 movements were included. To familiarize the subject with the vibration sensation testing procedure, a tuning fork was struck and then held against the clavicle until the subject could no longer feel the vibration. At that point, the subject verbally reported “gone”. This procedure was repeated by placing the tuning fork proximal to the nailbed of the great toe. The time between the striking of the tuning fork and when the subject reported “gone” was recorded. Individuals who perceived the vibration for less than 8 s were excluded from the study. Binocular vision, with corrected lens if needed, was tested with subjects reading a sentence on a paper at a distance of 40 cm. Individuals who were able to read the sentence scored 20/50 or better. Subjects with vision below 20/50 were excluded from the study.

In addition to sensory testing, cognitive and balance assessments were also performed in older adults. Cognition was examined with Mini-Cog test (Borson et al., 2000). Individuals with scores indicating impaired cognition were excluded from participating in the experiment. A series of balance tests were conducted using the protocols developed by Duncan et al. (1992) for the Functional Reach (Duncan et al., 1992), by Podsiadlo and Richardson (1991) for the Timed Up and Go, and by Bohannon et al. (1984) for the single leg stance. Balance scores in older adults were required to be within normal limits to rule out individuals at risks of falls. Cut-off values were determined based on scores reported in previous studies. Functional Reach was below 29 cm (Brauer et al., 2000). The Timed Up and Go was at 12 s (Shumway-Cook et al., 2000). The single leg stance was 14 s (Bohannon et. al, 1984; Heitmann et al., 1989).

Experimental protocol

Subjects stood barefoot on a force platform (AccuSway, AMTI, Inc.) with their feet oriented forward and outward and the second metatarsal at 15 deg from the mid-sagittal plane. The midpoints of the heels were separated by a distance of 10% of body height. To ensure consistent foot positioning between trials, an outline of the feet was traced on a paper covering the force platform.

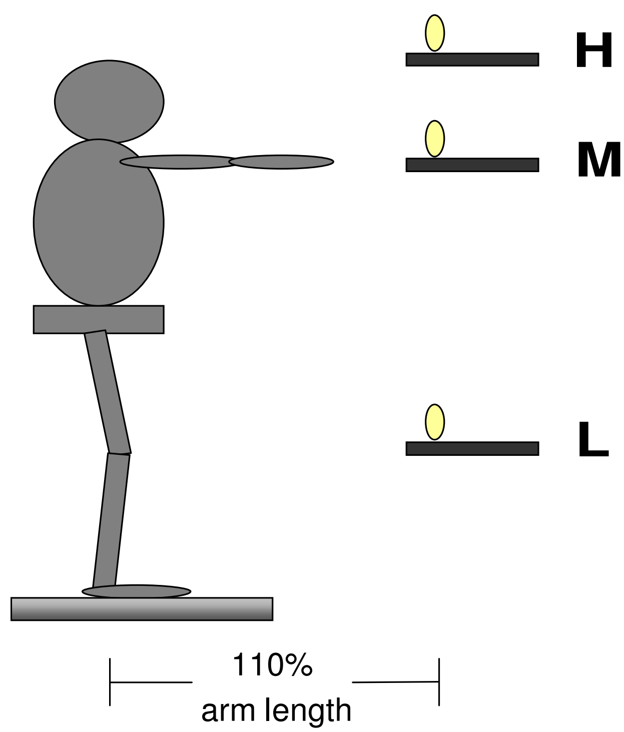

Figure 3.1 — Schematic representation of the experimental set up.
Target heights: H (high), M (medium), and L (low).

Figure 3.1 presents the schematic set-up for the experiment. The reach target was a cylinder (5 cm in diameter, 15 cm in height, and 300 g in weight), placed at 110% of arm's length away from the right lateral malleous and was aligned with the reaching shoulder in the para-sagittal plane. There were three target heights determined by the level of the base of target: at the top of the head (high), at the height of the shoulder joint (medium), and at the level of the knee joint (low). Subjects reached to the target with the dominant or non-dominant hand. Testing order of conditions was randomized across subjects.

Prior to the beginning of each trial, subjects stood upright with their arms at 0 deg of shoulder flexion and abduction, 0 deg of elbow flexion and wrist flexion, forearm in semi-supination, thumbs pointing forward, and fingers fully extended. Upon hearing a "go" command, subjects initiated the movement at a self-chosen time. They were instructed to "reach, grasp the target, and return with the target in the hand to the upright posture as fast and accurately as possible". Since emphasis was placed on both speed and precision, these were not maximum speed movements. No specific instruction regarding movement strategies was given. Subjects were reminded to use a whole hand grasp to acquire the target and keep their feet in place during the task. Subjects performed 4 to 6 practice trials to become familiar with the task. Resting periods of 2 min were provided every 10 min during data collection to minimize fatigue. Three trials were performed for each condition for a total of 18 trials. Each trial lasted 8 s.

Data acquisition and analysis

Kinematics of bilateral wrist, shoulder, and hip movements were recorded using a three-dimensional motion capture system (Motion Star, Ascension Technology, Inc.). Sensors were placed at the wrist (midpoint between the radial and stylus processes over the dorsal surface), shoulder (lateral to acromioclavicular joint), and hip (greater trochanter) joint. Custom-written LabVIEW programs (National Instruments, Inc.) were used to calibrate the data recording system and collect the data. Data were then processed and analyzed with costumed written Matlab programs (Matlab Version 6.0, The MathWorks, Inc.). The raw data were sampled at 100 Hz. A low-pass, fourth-order Butterworth digital filter at 6 Hz, 5 Hz, and 6 Hz was used for filtering data at the wrist, shoulder and hip joint, respectively. The filtering frequency was determined using the residual analysis of raw data (Winter, 1990). Hand trajectory data were obtained from the wrist sensor. Onset and offset of movements were scored with a threshold corresponding to 5% of peak velocity.

Primary dependent variable

Linearity of hand trajectory: Linearity of hand trajectory (*Dmax/D*) was obtained using the measure proposed by Atkeson and Hollerbach (1985). The distance (*D*) of the trajectory traveled by the hand in three-dimensional space (red line in Figure 3.2) was calculated. The straight line jointing the start and end points of the hand trajectory (black line in Figure 3.2) was interpolated. The maximum perpendicular distance (*Dmax*) from this straight line to the hand trajectory was calculated (blue line in Figure 3.2). Linearity of hand trajectory was quantified by the ratio of *Dmax/D*.

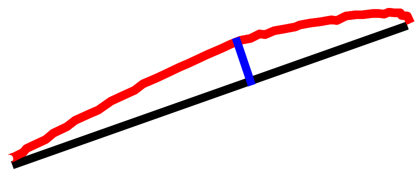

Figure 3.2 — Calculation of linearity of hand trajectory (*Dmax/D*). *D* corresponds to the distance of hand trajectory in three-dimensional space during reaching ( ). The straight line joining the start and end point of hand trajectory was interpolated ( ). *Dmax* corresponds to the maximum perpendicular distance from this straight line to the hand trajectory ( ).

<u>Secondary dependent variables</u>

(1) <u>Hand movement time:</u> Time between the onset and offset of hand reaching movements corresponded to hand movement time.

(2) <u>Hand peak velocity:</u> Peak values of hand tangential velocity profiles during reaching movements were determined.

(3) <u>Maximum trunk flexion:</u> Trunk flexion was determined from angular displacement of the line joining the reaching shoulder and the hip on the same side in the sagittal plane (Figure 3.3A). The maximum trunk flexion value during reaching was determined.

(4) <u>Peak trunk flexion velocity:</u> The first derivative of trunk flexion positional data corresponded to trunk flexion velocity. Peak value of trunk flexion was determined.

(5) <u>Maximum trunk rotation:</u> Trunk rotation was determined from the angular displacement of the line connecting both shoulders in the horizontal plane (Figure 3.3B). Maximum value of trunk rotation during reaching was identified.

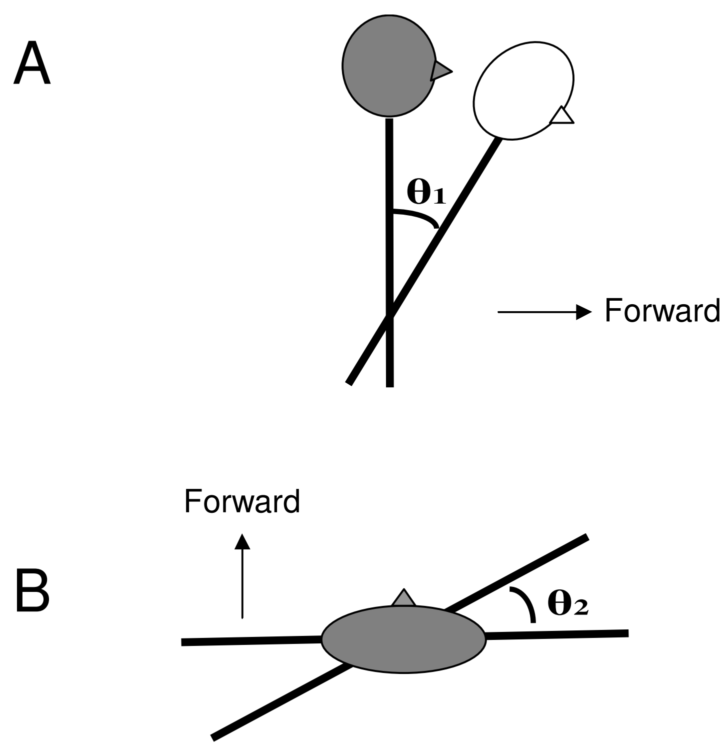

Figure 3.3 — Stick figures illustrate trunk flexion (**θ1**) in the sagittal plane (A) and trunk rotation (**θ2**) in the horizontal plane (B).

Statistical analysis

This experiment was a repeated measure design with age (young, older) as the between-subject factor, target height (high, medium, low) and hand used for performing the task (dominant hand, non-dominant hand) as the within-subjects factors. Means from all trials within each condition were submitted for statistical analysis with SPSS version 16. Post-hoc analysis was performed using Tukey's LSD method for the effects of age and hand, and adjusted using the Bonferroni method for the effect of target height. The effect size was evaluated using partial eta squared (η_p^2), which is a measure commonly used in experiments with repeated measure designs. Partial eta squared (η_p^2) assesses the relative contribution of each factor (independent variable) on the response variable (dependent variable) (Britz et al, 2009; Cohen, 1988; Mayer et al., 2006; Starr et al., 2004). Values of η_p^2 reported in previous studies with repeated measure designs are shown in Appendix C for reference. Independent t-tests were performed to compare the anthropometric parameters between young and older subjects. The level of statistical significance was set at $p<0.05$.

Results

Kinematics of hand movements

(1) Secondary variable: hand movement time

Across all target heights, older adults had significantly longer hand movement time than young adults ($F_{1, 28} = 7.3$; $p<0.05$; $\eta_p^2 = 0.21$) (Figure 3.4). Moreover, in older adults only, reaching with the non-dominant hand was associated with longer movement time compared to movements made with the dominant hand (hand effect: $F_{1, 28} = 9.7$; $p<0.01$; group by hand effect: $F_{1, 28} = 5.3$; $p<0.05$). Post-hoc comparisons revealed a significant hand effect but only in older adults (LSD method: $p<0.001$; $\eta_p^2 = 0.36$). Hand movement time was significantly varied depending on target heights ($F_{1, 28} = 191.5$; $p<0.001$; $\eta_p^2 = 0.87$). For both young and older adults, reaching to high or low targets was associated with longer hand movement time compared to reaching to medium height targets (Post-hoc with Bonferroni method: $p<0.05$) (Figure 3.4).

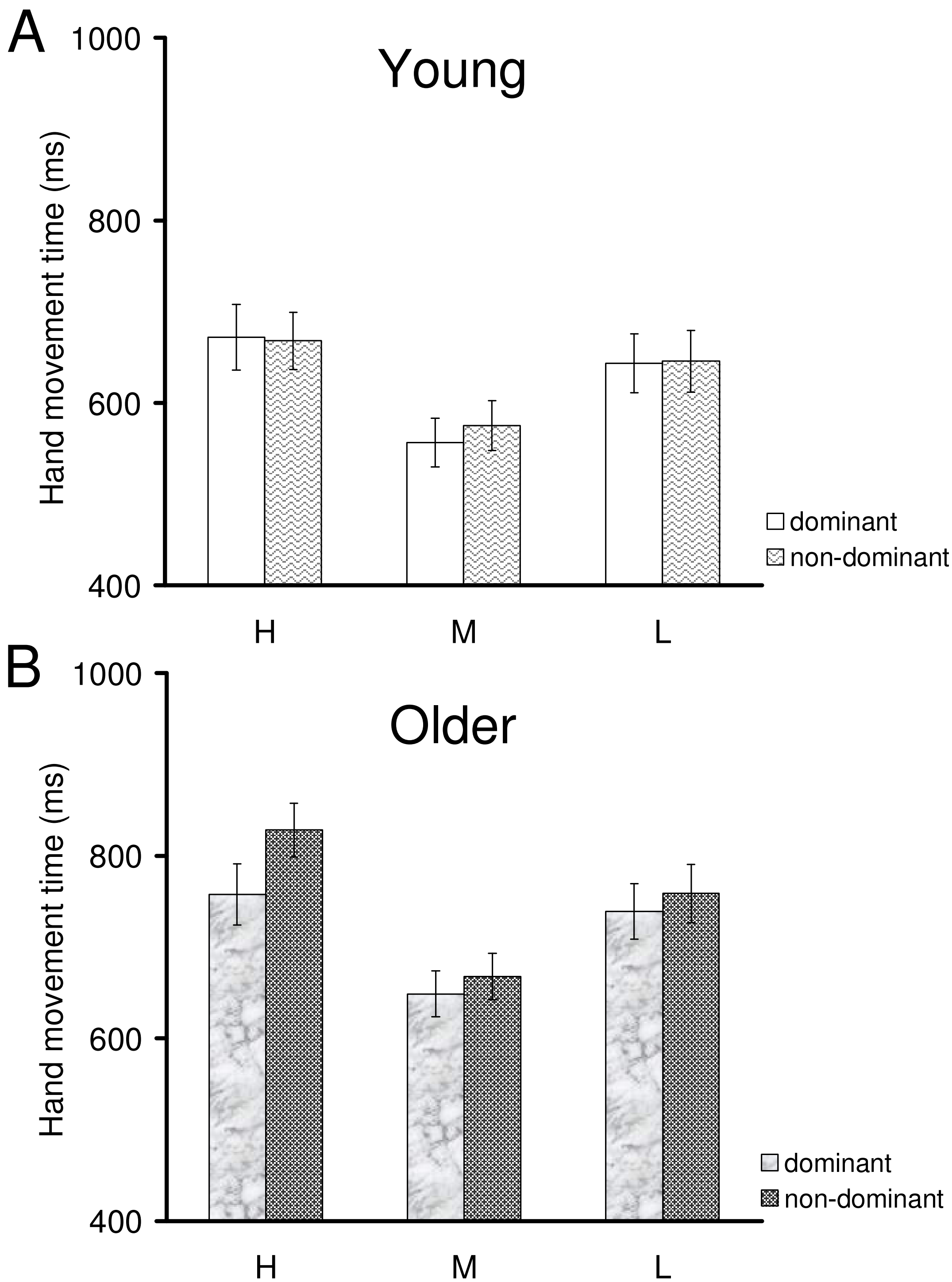

Figure 3.4 — Mean (± SE) hand movement time in young (A) and older (B) adults. Significant effects of group, height, hand, group X hand, $p<0.05$.

(2) Secondary variable: hand peak velocity

No age effect was found for hand peak velocity. As shown in Figure 3.5, for both young and older adults, hand peak velocity significantly varied with target height ($F_{1,\,28}$ = 174.4; p<0.001; η_p^2 = 0.78) (Post-hoc with Bonferroni method, p<0.05). Hand peak velocity was also not affected by the hand used for performing the reaching movement.

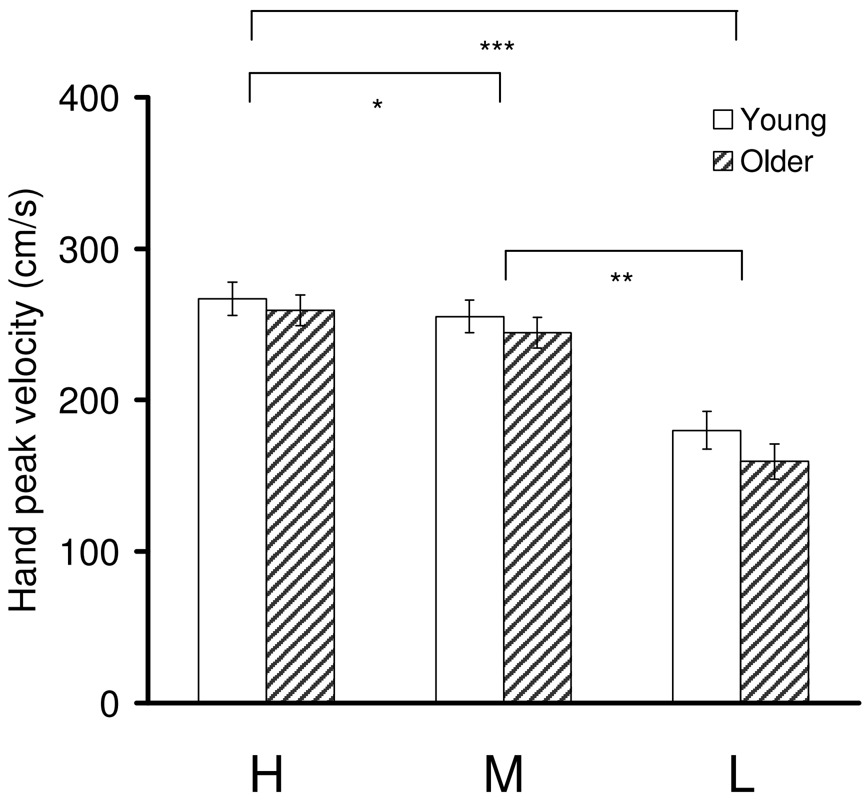

Figure 3.5 — Mean (± SE) hand peak velocity in young and older adults. Data collapsed across hand conditions. * <0.05; ** p<0.01; *** p<0.001.

(3) <u>Primary variable: linearity of hand trajectory</u>

Age did not significantly influence linearity of hand trajectory. However, in both young and older adults, linearity of hand trajectories did vary with the target heights ($F_{1, 28}$ = 12.9; p<0.01; η_p^2 =0.26) (Figure 3.6). Post-hoc comparisons confirmed that hand trajectories were significantly more curved during reaching to the low compared to medium and high targets (Bonferroni method, p<0.05; η_p^2 = 0.32). Across all target heights and groups, reaching with the dominant versus non-dominant hand did not affect linearity of hand trajectories.

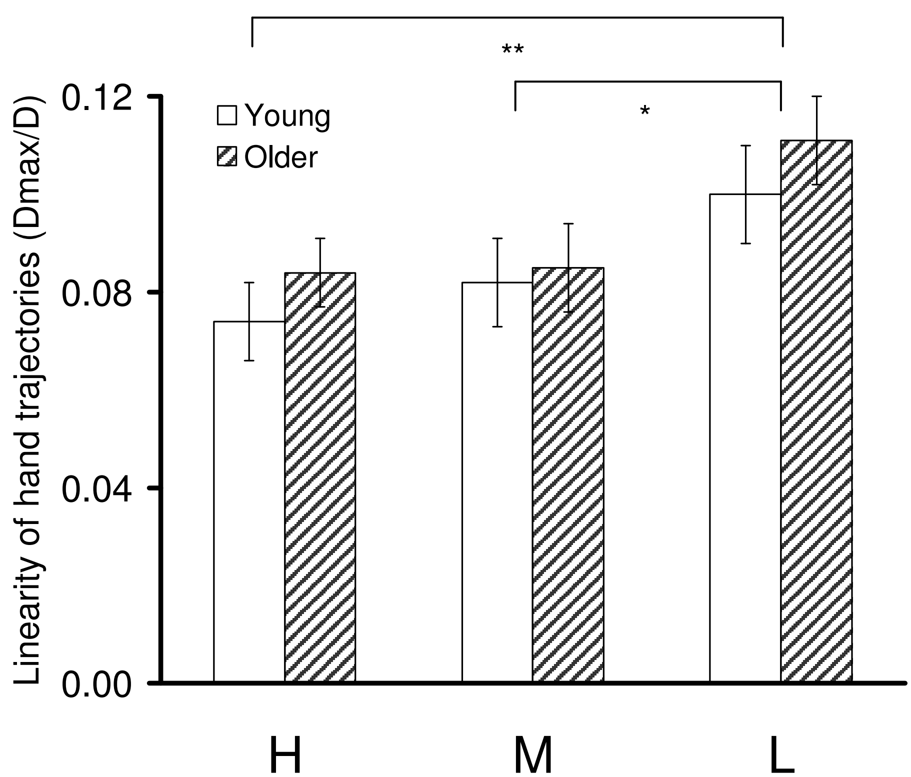

Figure 3.6 — Mean (± SE) linearity of hand path in three-dimensional space. Data collapsed across hand conditions. * p<0.05; ** p<0.01.

Kinematics of trunk movements

(1)Secondary variable: Maximum trunk flexion

For both young and older adults, maximum trunk flexion was significantly greater during reaching to the low target ($F_{1, 28}$ = 1535.8; p<0.001; η_p^2 = 0.17) (Figure 3.7). During reaching to the low target, older adults had reduced maximum trunk flexion compared to young adults (group by height effect: $F_{1, 28}$ = 10.1; p<0.01; η_p^2 = 0.26). Post-hoc comparison revealed that this difference between groups at low target was significant (LSD method, p<0.05; η_p^2 = 0.16). No age differences were found at high and medium height targets. Maximum trunk flexion was not affected by the hand used for reaching.

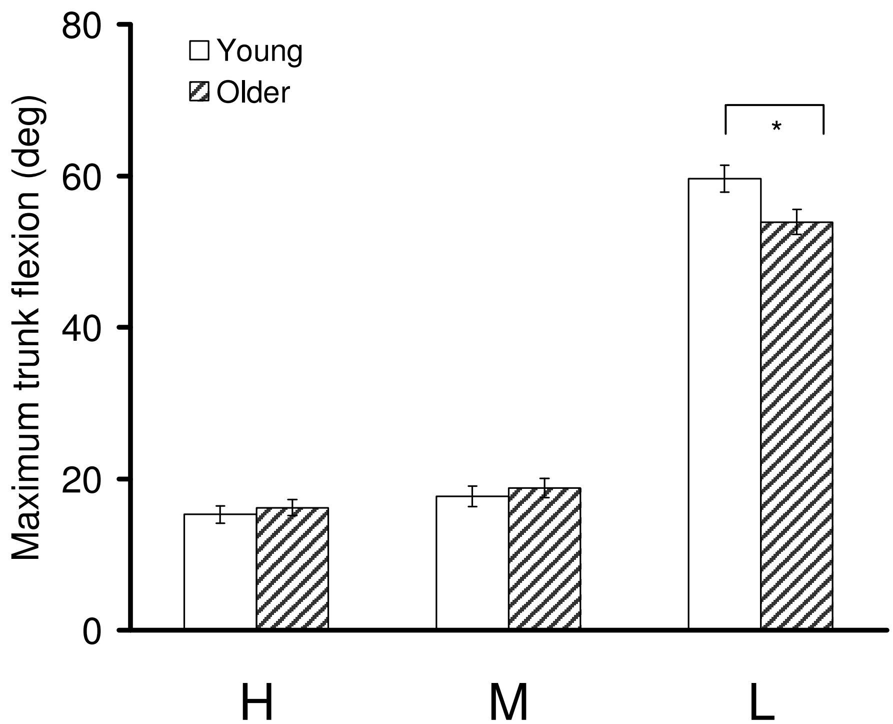

Figure 3.7 — Mean (± SE) maximum trunk flexion in young and older adults. Data collapsed across hand conditions. * p<0.05.

(2) Secondary variable: Maximum trunk rotation

Age did not affect maximum trunk rotation involved during the reach. For both young and older adults, maximum trunk rotation significantly increased to extend the reach as target height increased ($F_{1, 28}$ = 10.1; p<0.01; η_p^2 = 0.75) (Figure 3.8). Maximum trunk rotation was not significantly different when reaching with the dominant versus non-dominant hand.

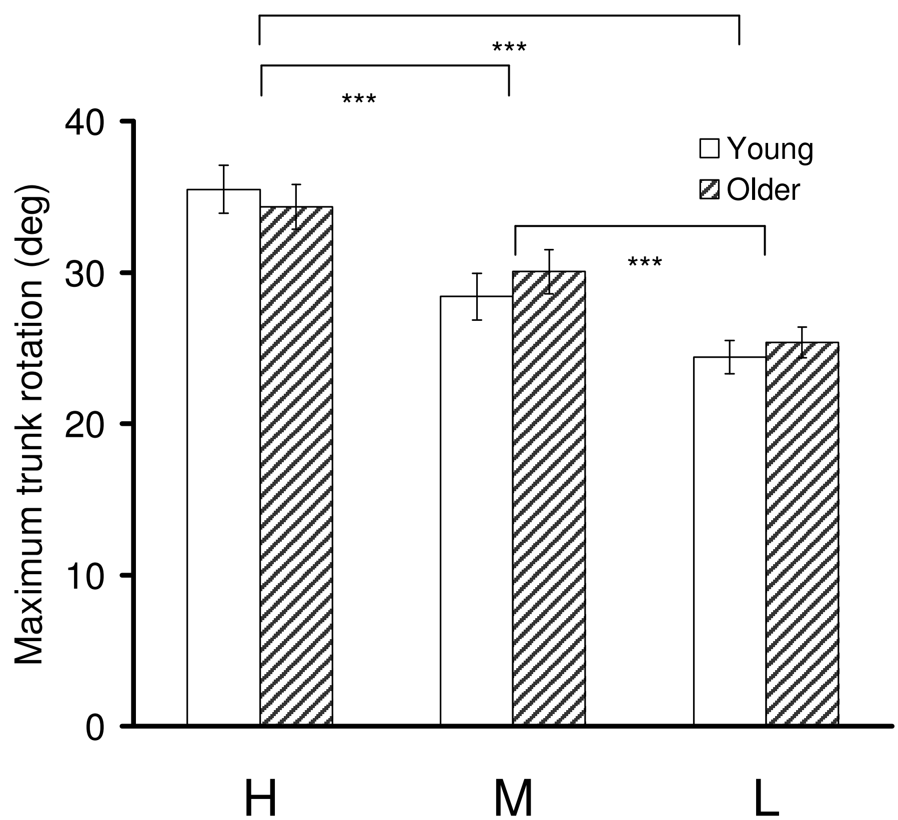

Figure 3.8 — Mean (± SE) maximum trunk rotation during reaching movements made towards targets at different heights. Data collapsed across hand conditions. *** p<0.001.

Discussion

The present study examined age differences in the kinematics of arm and trunk movements during standing reach. The effects of the target height and the hand used to perform the task were also examined. The results did not support the first primary hypothesis that during the performance of standing reach, older adults are able to maintain relatively straight line arm movement trajectories which do not significantly differ from their younger counterparts. In support of the other primary hypothesis, both young and older adults produced hand trajectories which were more curved during reaching to low targets than to medium and high targets. Variations in the straightness of hand trajectories with target heights reflect the influence of moving a large mass on the formation of hand trajectories. In support of the other secondary hypotheses, older adults showed longer and more asymmetric hand movement times compared to young adults, indicating aging is associated with increased asymmetry in upper limbs motor performance. As hypothesized, older adults reduced the amount of trunk flexion during reaching to low targets. Thus, the ability to incorporate trunk flexion movement during standing reach is affected by age.

Curvature of hand trajectories: Primary hypothesis

Since the findings by Morasso (1981) based on simple shoulder and elbow flexion and extension in a horizontal plane, roughly straight hand trajectories are widely viewed as a constraint used by the CNS in planning arm movements. Sergio and Scott (1998) showed that in young seated subjects, the curvature of hand trajectories for arm movements in the horizontal plane was overall quite small, despite differences in movement directions or amplitudes. In their study, *Dmax/D* values were on average from 0.03 to 0.11, which are similar to the range of curvature found in the present study (0.7 at high target and 0.11 at low target), and in the studies by Atkeson and Hollerbach (1985) (0.5 to 0.13 for sagittal plane movements), Desmurget et al. (1997) (0.06 to 0.10 for unconstrained and 0.02 to 0.04 for constrained arm movements in the horizontal plane), and Pozzo et al. (2002) (0.07 to 0.10 in conditions of different movement speeds and distances during standing reach). Therefore, hand trajectories are relatively straight across a variety of movement tasks.

It was expected that older adults would show straighter hand trajectories based on previous findings by Paizis et al. (2008). However, there were no age differences in the straightness of hand trajectories during standing reach which required subjects to maintain postural stability. This suggests that well-documented age-related declines in postural control (Horak, 2006; Maki & McIlroy, 2006) did not affect the ability of the motor system to plan straight hand trajectories in three-dimensional movements. On the other hand, for both groups, hand trajectories were more curved during downward reaching to low targets than forward to medium height targets or upward to high targets. As presented in Chapter 2, low targets were associated with the largest anticipatory postural adjustments and most irregular COP trajectories during movement execution. It is conceivable that increased curvature of hand trajectories may be related to higher demands for postural stability and multi-joint coordination when reaching to low targets. Such tasks require a substantial amount of trunk movement in the reach. Other studies of standing reach have shown that movement speeds, target distances, or the base of support configuration do not influence the curvature of hand trajectories (Berret, 2009; Pozzo et al., 2002). Thus, it may be concluded that variations in the straightness of hand trajectories across different target heights are not solely due to the task constraints of maintaining standing balance but also result from the need to coordinate multiple body segments, particularly the trunk.

By comparing experimental and model simulation data, Flash (1987) proposed that deviations in hand trajectories from a straight path resulted from difficulties of the motor system to control the dynamics of the body segment, including the inertial and viscous-elastic properties. In the present experimental tasks, the reach was extended with trunk flexion at low targets. With the need to move such as large mass, controlling the dynamics of body segments during movement execution was more challenging. Similarly, increased curvature of hand trajectories with increased trunk rotation have been observed by Pigeon et al. (2003a). They concluded that forces generated by the motor system to produce straight hand trajectories may not be sufficient when there are substantially large trunk movements. Current results also demonstrate that the formation of hand trajectories is influenced by the associated trunk displacement in both young and older adults.

Surprisingly, current results showed that the ability to produce straight hand trajectories is preserved in older adults. Furthermore, linearity of hand trajectories was modulated with target height in a similar manner for both age groups. Previous studies examining arm movements in older seated subjects have found increased variability in hand trajectories (Darling et al., 1989; Ketcham et al., 2002). On the other hand, older adults make straight hand trajectories when reaching is performed from a standing position, which may be a strategy to increase postural stability (Paizis et al., 2008). In the present study, older adults recruited were generally active, healthy, and live independent in the communities. Future studies with a larger sample of older adults with different functional capacities may reveal larger age differences.

Age-related increase in asymmetric manual performance: Secondary hypothesis

In the present study, longer hand movement time during reaching with the non-dominant than dominant hand was found but only in older adults. Previous studies typically have found age-related increases in manual asymmetry in more complex tasks that require attention, speed, or accuracy (Francis & Spirduso, 2000; Teixeira, 2008). However, in the current study, the tasks employed did not impose high accuracy constraints. The size and shape of the target resembled those commonly seen in the surrounding environment such as door or pot handles. In addition, whole hand grasp used here to grasp the object is frequently used to acquire objects during daily activities. Therefore, the present study demonstrated that increased asymmetry in upper limbs motor performance with age is also present even in familiar, functional tasks. Similar to the hypothesis proposed by Brown and Jaffet (1975), current findings suggest that after long-life preferred use of the dominant hand, there is an increased asymmetry in movements involving postural stabilization and multi-joint coordination.

Effect of age on the utilization of trunk movements in the reach: Secondary hypothesis

Despite comparable hand trajectories during reaching movements in both age groups, older adults accomplished this by using an altered kinematic strategy. There was seen as a small but significant reduction in trunk flexion when reaching to low targets.

Similarly, others have shown that older adults reduced trunk angular displacements compared to young adults while reaching forward maximally in standing (Kozak et al., 20030 and upward (Cavanaugh et al., 1999). This reduction in trunk flexion with age may have significant functional implications. For instance, Hilliard et al. (2008) recently reported that the range of active trunk rotation predicts the prevalence of falls in older adults. Therefore, a reduction in trunk movement with age is associated with declines in postural control.

Altered trunk control in older adults may be also related to age-related declines in sensorimotor and musculoskeletal function, such as muscle strength (Alexander et al., 1997; Puniello et al., 2001), trunk reposition sense (Goldberg et al., 2005), or spinal flexibility (Alaranta et al., 1994; Troke et al., 2005). Further, smaller trunk displacements may enhance the stabilization of the head in space and consequently, reduce potential ambiguities in the interpretation of sensory inputs for postural control (De Fabio & Emasith, 1997).

Implications

The component of voluntary trunk control should not be overlooked in rehabilitation programs to improve upper limb motor function in the elderly population. The trunk commonly takes part in the reach when the target distance is beyond arm's length. Some training programs have suggested restricting the trunk movements during rehabilitation for the upper limb function in stroke patients (Michaelsen et al, 2006). However, restricting the trunk movements would further enhance the disuse or decline in the ability to use this component with age. Recent studies have shown that after training, older adults are able to improve their ability to arrest trunk movements induced by unexpected perturbations to upright stance (Grabiner et al., 2008), suggesting that older adults can learn to exert greater control of trunk movements. Stroke patients have shown greater improvement in hand function following training with movement tasks incorporating arm and hand together compared to training with the arm and hand moving separately (Adamovich et al., 2008). These findings further support the notion proposed here that reaching movements involving multi-joint coordination should be practiced as a whole, including all body segments required to accomplish the task.

Limitations

The small sample size in the present study may be considered a limitation that precludes generalization of current findings. In the present study, repeated measures design permitted each subject to serve as his/her own control and reduced the variability associated with individual differences. This approach allows for more economical and powerful analysis despite smaller than usual subject groups (Fitzmaurice et al., 2009). Moreover, practice effects of the task over repeated trials were minimized because the order of conditions was randomized across subjects. Nevertheless, a larger group of older subjects, including more frail individuals, will further expand current findings to the general elderly population.

The straightness of hand trajectories was calculated in three-dimensional space. While reaching to higher targets involved more trunk rotation, reaching to the low target utilized greater trunk flexion. Therefore, it is possible that the influence of trunk movements on the curvature of hand trajectories could vary in the horizontal and sagittal plane. Such findings, however, will further support that curved hand trajectories are related to the trunk movement employed to extend the reach.

Different target heights altered the contribution of arm versus trunk in the reach. It may be argued that variations in the curvature of hand trajectories across target heights are due to differences in the reach distance. However, studies of arm movements performed in the horizontal plane (Morasso, 1981; Sergio & Scott, 1998) and whole body reaching movements (Pozzo et al., 2002) have demonstrated that the straightness of hand trajectories is not affected by the reach distance (Pozzo et al., 2002; Berret et al., 2009). In the present study, increased curvature of hand trajectories during reaching to low targets may reflect the complexity of the underlying motor control processes since reaching to low targets involves the coordination of multiple joints and with the displacement of a large mass of the trunk.

The kinematics of lower extremity movements were not recorded. Different movement strategies for coordinating arms, trunk, and legs could be utilized during reaching, particularly to low targets in older adults. For instance, a reduction in trunk flexion can be accompanied by increased flexion at the hips and/or knees. It is not known whether different movement strategies would affect the straightness of hand trajectories.

It is possible that the measure of hand trajectory linearity did not totally reflect the characteristics of hand trajectories in the present study. Various measures have been used to quantify the shape of hand trajectories, such as path length ratio (ratio of the total path length divided by the distance of the straight line connecting the start and end position) (Archambault et al., 1999; Biess et al., 2007; Ma & Feldman, 1995), curvature of hand trajectories (ratio of maximum deviation along the trajectory from the straight line connecting the start and end position divided by the distance of this straight line) (Atkeson & Hollerbach, 1985; Desmurget et al., 1997; Pozzo et al., 2002), whole deviation (area encompassed by the actual hand trajectory to the start to end straight path) (Paizis et al., 2008), and the ratio of the minor axis divided by the major axis of the hand trajectory (major axis defined as the largest distance between any two points in the trajectory, minor axis defined as the largest distance, perpendicular to the major axis, between any two points in the trajectory) (Sainburg et al. 1993). Despite different calculation methods, these variables are all used to measure the straightness of hand trajectories. Archambault et al. (1999) used path length ratio as they found that in some cases hand trajectories could be S-shaped instead of arched. Path length ratio has also been used to measure the quality of arm movements in stroke patients, with smaller path length ratio indicating improvement in arm motor function (Broeren et al., 2007; Colombo et al., 2007). Sergio and Scott (1998) argued that various measures representing the shape of hand trajectories revealed similar results for arm movements made with different speeds, directions, and distances. To what extent these different variables reflect the same processes underlying motor control has not been explored.

The present study has other limitations, including instruction set, postural responses relative to one's maximum capacity, nature of a speeded task, within-subject variability in performance, and potential bias of data processing and analysis. These issues will be addressed in the section of general discussion (Chapter 5).

Future Studies

Based on recent findings from principal component analysis of voluntary movements, it has been suggested that two primary modules for coordinating multiple joints are used to control the COM and hand trajectories, respectively (Alexandrov et al., 1998; Krishnamoorthy et al., 2004; Berret et al., 2009). Therefore, future research using this analytical approach may identify how age affects these two primary components during whole body movement tasks.

Further clinical studies are need to investigate whether or not the characteristics of hand trajectories and coordination of the trunk with the arm will be altered following rehabilitation programs in older adults with impaired motor and postural control due to diseases (e.g. stroke or Parkinson's disease). Experimental designs using double blind randomized control trials will further validate the findings. Different treatment programs can also be compared to identify effective intervention for improving multi-joint whole body movements.

Conclusions

- Despite the importance of limb-posture coordination during functional tasks, this study was the first to examine age differences in arm movements during standing reach to various regions in the workspace and with the dominant versus non-dominant hand. The present study expands previous findings based on two-dimensional arm movements made from a seated position. The need to coordinate multiple joints and control postural stability likely contribute to the increased curvature of hand trajectories during reaching to low compared to higher targets for both young and older adults.

- Older adults show longer and more asymmetric hand movement time during reaching even though the accuracy constraint was low and target acquisition involved a familiar whole hand grasp. Thus, age-related increase in asymmetric upper limb motor control is not limited to tasks that require high precision, attention, and speed.
- Although no age differences are present in the straightness of hand trajectories, older adults accomplish the task with altered kinematic strategy as evident by reduced forward trunk displacement during reaching. Thus, trunk control is an important component that needs to be integrated in training programs aimed to improve arm movement control in older adults, particularly in tasks requiring control of standing balance.

Chapter 4

Contextual Effects of Grasp versus Point on Center of Pressure during Standing Reach in Young and Older Adults

Introduction

The maintenance of balance is essential to successfully accomplish functional tasks. Following external perturbations, the CNS employs compensatory postural responses triggered by sensory feedback to correct balance. Anticipatory postural adjustments (APAs) are generated to counteract the perturbations associated with the forthcoming movements from reaction forces and changes in the body configuration. Numerous studies have implicated age-related changes in sensory (Era et al., 1996; Lord et al., 1991; Whipple et al., 1993), neuromuscular (Lord et al., 1991; Moreland et al., 2004), and cognitive processes (Brauer et al., 2002; Laufer et al., 2006; Lord et al., 1991; Maki & McIlroy, 2007) in the deterioration of postural responses in older adults. Activation of postural muscles is frequently delayed (Man'kovskii et al., 1980), with disrupted recruitment sequences and altered amplitudes (Allum et al., 2002; Bleuse et al., 2006; Woollacott & Manchester, 1993). Following external perturbations to upright stance, older adults are less able to counteract the imposed perturbations (Gu et al., 1996) and show larger excursions of the trunk (Pavol et al., 2001; Rogers & Mille, 2003) and COP displacements relative to young subjects (Bugnariu & Sveistrup, 2006) Older adults are also more likely to produce a stepping response or use hand grasping to recover balance (Mille et al., 2003). These inadequate postural responses contribute to increased difficulties in maintaining balance during daily activities in older adults and are thought to increase risk for falls in this population (Ganz et al., 2007).

The preservation of standing balance necessitates the center of gravity (COG) to be positioned within the base of support (BOS). To achieve this goal, the central nervous system (CNS) activates postural muscles to shift the center of pressure (COP) and consequently, keeps the COG from moving out of the BOS (Winter et al., 1996). With age, the maximum ranges for shifting the COP without moving the feet, i.e. stability limits, are reduced in the forward, lateral, and backward directions (Binda et al., 2003; Holbein-Jenny et al., 2007; King et al., 1994; Mille et al., 2003). Clinical tests commonly used for measuring the stability limits require the individual to reach (Duncan et al., 1992) or lean maximally (King et al, 1994; Holbein-Jenny et al., 2007) while holding the posture at the end of the reach. However, functional reaching tasks performed during daily activities frequently involve interacting with objects in the surrounding environment and do not necessarily require one to maintain the posture following reaching. To date, it is not known whether postural control in older adults is affected by the movement context, i.e. the properties of objects in the outside world and the prevailing environmental condition (Vetter & Wolpert, 2000). Wolper and Ghahramani (2000) suggested that when planning a movement, the CNS needs to generate the predicted sensory feedback based on the current context. Actual sensory feedback is compared with this prediction whereas errors signals from this comparison are used to update the estimated context and correct the subsequent movement. From this perspective, the movement context pertaining to interacting with the object at the end of the reach can influence how the CNS controls posture and limb movements.

Indeed, there is evidence supporting the view that the characteristics of a reaching target can alter postural responses in a feedforward manner. In a study by Nana-Ibrahim et al. (2008), standing subjects performed fast aiming movements to different diameter targets. It was found that while aiming precision was comparable across different targets, longer APA duration was observed for the medium sized than larger or smaller targets. Likewise, Bonnetblanc et al. (2004) reported that during fast aiming movements, the patterns of anticipatory postural muscle activity varied with the target sizes. As the target became smaller, the magnitude of the muscle activity in erector spine increased whereas those in lower extremity muscles decreased. They concluded that the characteristics of the pointing task varied by the target size were integrated in the commands for postural responses in a feedforward manner. Taken together, the above findings indicate that, at least for target size, an internal representation of the target/object characteristics is formulated and used in the programming of appropriate postural responses.

When the movement context involves target manipulation at the end of reach, such as turning a door knob or pulling a curtain cord, the perturbations from the manipulation component are also anticipated. Wing et al. (1997) instructed standing subjects to grasp a handle between thumb and index finger, and pull or push either a variable or a fixed load in a horizontal direction. It was shown that, in all conditions, increases in grasp forces and ground reaction torques preceded any detectable rise in the load force. In addition, rates of change in the grasp forces and the ground reaction torques were correlated, indicating that grasp and postural adjustments were represented by the same motor program and were pre-planned in anticipation of the perturbations induced by manipulating the load. Similar results of tightly coupled relationships between hand grasp forces and APAs represented by ground reaction forces and torques, and COP displacements have also been reported when grasping is performed from a standing position (Forssberg et al., 1999) and during gait initiation (Diermayr et al., 2008). Taken together, these findings suggest that the CNS take into account the dynamics involved during target manipulation (e.g. the forces generated by the motor system and the characteristics of the object being held in the hand) when planning feedforward postural adjustments.

While above findings demonstrate that the programming of APAs during standing reach is influenced by the movement context related to the objects with which one interacts, whether this type of movement context also affects the control of dynamic balance following movement onset has not been explored. The present study was designed to investigate the impact of movement context on postural control in young and older adults. To this end, standing subjects performed either pointing versus grasping at the end of the reach. The target was placed at 90 percent of each subject's functional reach distance in the forward and lateral direction. This allowed the influence of the movement context to be examined proportional to each subject's maximum functional capacity. It was expected that grasping would present greater challenges to postural control compared to simply pointing since subjects were required to exert forces at target acquisition and to maintain their COP closer to the boundaries of the BOS for longer durations under the grasping condition. The primary variable for measuring postural control was COP trajectory linearity. The control of COP trajectory along a straight path has been measured in dynamic balance tests using the Balance Master system (NeuroCom International, Inc., Clackamas, OR) (Clark et al., 1997), with straighter COP trajectories during dynamic weight shifting tasks indicating better postural control (Tsang & Hui-Chan, 2004). Other secondary variables included COP maximum displacement and COP peak velocity, which have been frequently used for assessing dynamic balance in older adults (Duncan et al., 1990; Holbein-Jenny et al., 2007; Paizis et al., 2008), and grasp duration and maximum force for examining grasp performance.

The primary hypothesis was that postural control measured by COP trajectory linearity would be affected by the movement context at the end of a reach in older but not young adults, regardless of the target direction. The secondary hypothesis was that older adults would show smaller COP displacement and slower COP peak velocity during the execution of both reach-point and reach-grasp conditions, reflecting an age-related reduction in stability limits (Binda et al., 2003; King et al., 1994; Holbein-Jenny et al., 2007). The other secondary hypothesis was that no differences in grasp parameters would be found between groups.

Method

Subjects

Eight young (age = 23.6 ± 3.0 years; 5 female and 3 male) and 10 older (age = 74.1 ± 4.8 years; 6 female and 4 male) volunteers participated in the present study. None of the subjects had been tested in the other experiment reported in this dissertation. Young subjects were students and staff from the University of Michigan. Older adults were recruited via advertisements in local newspapers. Using self-reports, all subjects were right-handed, ambulatory without use of an assistive device, and lived independently in the community. A short questionnaire was used during the recruitment processes (see Appendix A). Individuals with a history of diabetes, neurological, or debilitating musculoskeletal disorders were excluded. Informed consent was obtained from each subject prior to participation in accordance with the requirements by the Institutional Review Board at the University of Michigan.

Following each subject's consent, anthropometric parameters including body weight, body height, and arm length were recorded. Maximum reach distance in the standing position was then determined with the right arm reaching in the forward and the lateral direction respectively (Duncan et al., 1990; Newton, 2001). Position sense of bilateral great toes was examined following the protocol developed by Richardson (2002). The examiner grasped the medial and lateral surfaces of the great toe with thumb and index finger. Up and down movements were first performed with the subject's eyes open. With the subject's eyes closed, a series of 10 upward and downward movements at approximately 1 cm in amplitude and about 1 s in time was randomly administered for each great toe. A correct response was recorded when the subject perceived the movement and identified the direction correctly. Individuals who were not able to identify correctly 8 out of 10 movements were excluded from participating in the experiment.

<u>Experimental protocol</u>

Subjects stood barefoot in a comfortable position on a force platform (AccuSway, AMTI, Inc.). The starting posture required both arms to be positioned by the sides, shoulders at 0° of flexion and abduction, elbows and wrists at 0° of extension, forearms in a neutral position, thumbs pointing forward, and fingers fully extended. To ensure consistent foot positioning between trials, an outline of the feet was traced on a paper covering the force platform.

The reach target was a cylinder (5 cm in diameter, 15 cm in height) placed on a flexible stand at the height of the xiphoid process. There were two target directions: forward in the mid-sagittal and to the right in the frontal plane. The reach distance was measured from the right acromion process and equivalent to 90% of maximum reach distance in the forward or lateral direction.

After a “go” command, subjects initiated reaching movements at a self-chosen time with their right arm. They either grasped or pointed to the target, and then returned to the initial upright posture. Subjects were instructed to perform the task as fast and as accurately as possible. Since emphasis was placed on both speed and precision, these were not maximum speed movements.

In the pointing condition, subjects pointed to a square target (2.5 cm X 2.5 cm) outlined by a yellow tape. In the grasping condition, subjects were instructed to make a firm and quick grasp using their whole hand, similar to a hand shake. They were reminded not to pause or produce maximum grasp forces at target acquisition. Subjects grasped the target without removing it from the stand. The target stand was designed to be flexible to prevent subjects from leaning on it for support.

Subjects performed 2, 10 s practice trials for each condition. Reaching and returning movements were repeated for as many cycles as possible in a 20 s trial. One trial for each condition was collected. A rest period of 2 min was given every 10 min. There were 4 different task conditions which varied by the movement context at the end of reach (point versus grasp) and by target direction (forward versus lateral). The order of experimental conditions was randomized across subjects.

Data acquisition and analysis

The same equipment and software programs for data recording described in Chapter 2 were used. Three-dimensional kinematics and COP data were sampled at 100 Hz and filtered at 6 Hz with a fourth-order, zero-phase lag Butterworth filter. The first reach and return movement cycle from each trial was excluded for analysis as there was an anticipatory COP displacement prior to the onset of arm movement. Eight subsequent reach and return movement cycles were analyzed. Dependent variables within each reach and return movement cycle were calculated. A strain gauge was embedded inside the target to record grasp forces.

Primary dependent variable

COP trajectory linearity: This was calculated by dividing the cumulative distance traveled by the COP in the AP and ML direction between the onset and offset point (L) with the distance of the straight line connecting the onset and offset point (D) (Figure 4.1). A perfectly straight trajectory has a linearity ratio (L/D) equal to 1. A larger linearity ratio indicates increased deviations of COP trajectories from a straight path. Onsets and offsets of COP displacements were determined using a threshold of 1cm/s obtained from the first derivative of COP displacement data.

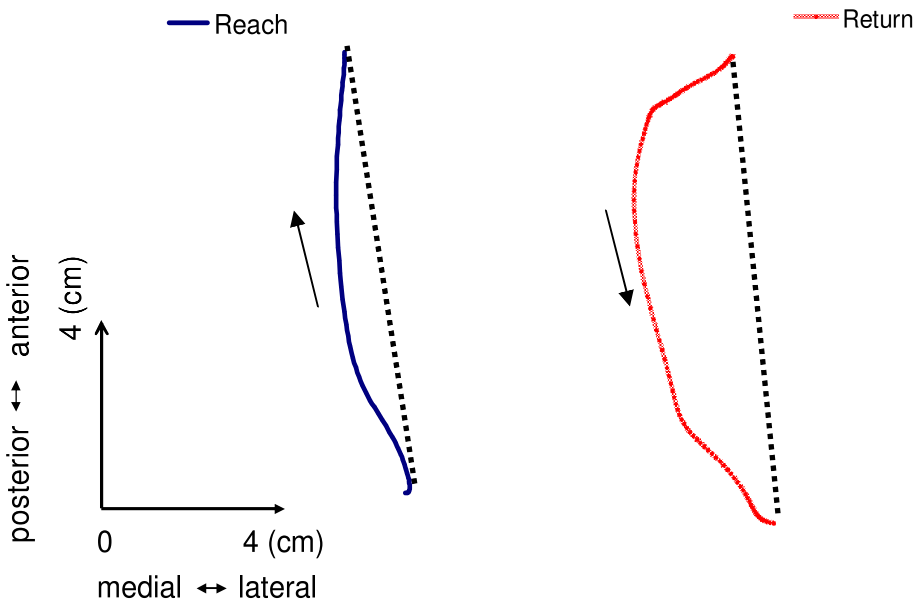

Figure 4.1 – COP trajectories during one reach (left) and return (right) movement cycle from one older subject. .... represents the straight line joining the onset and offset of COP trajectories; ⟶ indicates the movement direction.

Secondary dependent variables

(1) *COP maximum displacement:* This was obtained by calculating the difference between peak COP displacement in the anterior-posterior (AP) and medial-lateral (ML) direction for the forward and lateral reach, respectively (Figure 4.2). COP maximum displacement was normalized to each subject's BOS length for forward reach and the BOS width for lateral reach, respectively.

(2) *COP peak velocity:* Peak COP velocity values were obtained for COP displacement in the AP and ML direction for the forward and lateral reach, respectively.

(3) Maximum grasp force: Peak grasp force values were recorded from the strain gauge.

(4) Grasp force variability: This was calculated using the coefficient of variation (CV) of maximum grasp forces across movement cycles in the same trial. Grasp force variability was calculated to determine whether subjects consistently produced equivalent amount of forces in the same trial.

(5) Grasp duration: Grasp duration was determined as the time between the onset and offset of grasp forces as determined by a threshold equivalent to 5% of maximum grasp forces.

(6) Hand movement time: Duration between the onset and offset of hand velocity profiles was determined using a threshold equivalent to 20 cm/s.

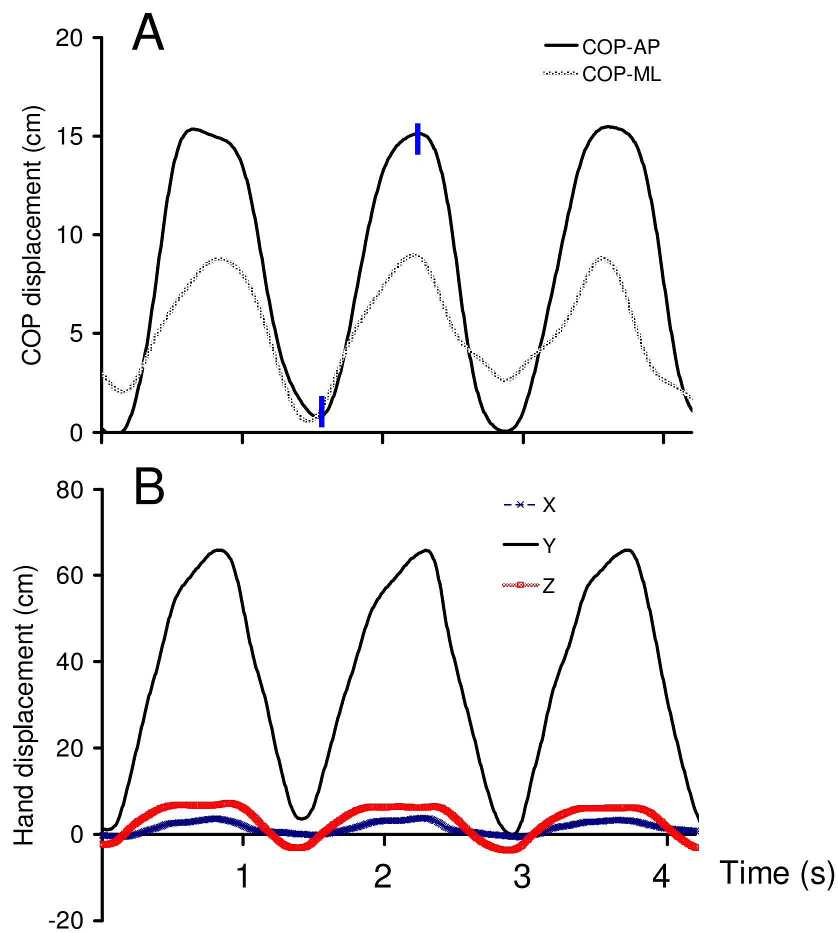

Figure 4.2 – COP displacement in the anterior-posterior (COP-AP) and medial-lateral (COP-ML) direction (A), and hand displacement in three dimensional coordinates (X, Y, Z) (B) from a young subject are shown. Blue bar (|) indicates peak COP displacement in the AP direction during a forward reach and point cycle.

Statistical analysis

This study was a repeated measures design, with age as the between subjects factor (young versus older), and movement context (point versus grasp), and target direction (forward versus lateral) as within subject factors. Dependent variables related to each reach and return movement were analyzed with Linear Mixed Model in SPSS (SPSS version 16.0, SPSS, Inc.). Post-hoc analysis was performed with Tukey's LSD method. Anthropometric parameters and target distances were analyzed with Student's *t*-tests for independent samples. The effect size was evaluated using partial eta squared (η_p^2), which is a measure commonly used in experiments with repeated measure designs. Partial eta squared (η_p^2) assesses the relative contribution of each factor (independent variable) on the response variable (dependent variable) (Britz et al, 2009; Cohen, 1988; Mayer et al., 2006; Starr et al., 2004). Values of η_p^2 reported in previous studies with repeated measure designs are shown in Appendix C for reference. The level of significance was set at $p <$ 0.05.

Results

Table 4.1 presents anthropometric parameters, BOS dimensions, and target distances (90% of functional reach distance). No significant differences between groups were found for these variables. Target distance was greater in young than older adults ($F_{1, 16} = 4.4$; $p = 0.05$). For both age groups, target distance was significantly greater in the forward than lateral direction ($F_{1, 16} = 58.4$; $p < 0.001$).

Table 4.1 – Anthropometric parameters, dimension of BOS, and target distance in young and older adults. *** $p<0.001$ for effect of direction.

	Young (mean ± *SE*)	Old (mean ± *SE*)
Body Height (cm)	168.3 ± 2.2	169.9 ± 3.1
Body Weight (Kg)	60.1 ± 3.6	79.3 ± 8.9
Arm Length (cm)	71.0 ± 1.3	73.8 ± 1.7
Base of Support (cm)		
Foot Length	25.3 ± 0.4	26.1 ± 0.7
Stance Width	33.0 ± 1.7	35.2 ± 1.9
Target distance (cm)		
Forward ***	98.0 ± 1.8	88.5 ± 3.6
Lateral ***	80.0 ± 2.9	73.5 ± 3.3

Secondary variable: Center of pressure maximum displacement

COP maximum displacements were significantly larger in young than older adults, regardless of the movement context or target directions ($F_{1, 16} = 9.7$; $p < 0.01$; $\eta_p = 0.40$) (Figure 4.3). Effects of movement context and target direction were not significant.

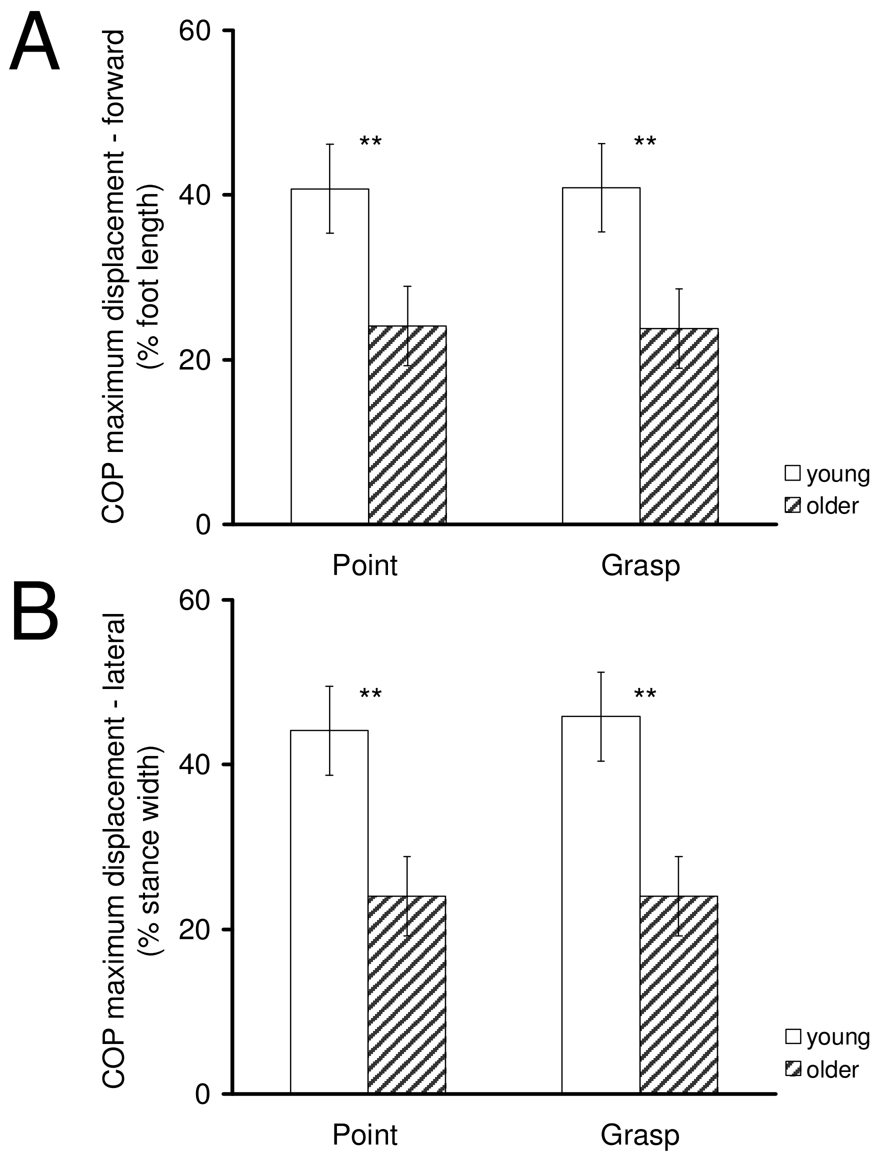

Figure 4.3 – Mean (±SE) COP maximum displacement during forward (A) and lateral (B) reach-point and reach-grasp condition in young and older adults. ** p<0.01.

Secondary variable: Center of pressure peak velocity

As shown in Figure 4.4, COP peak velocity decreased significantly with age during reach ($F_{1, 48} = 8.2$; $p < 0.05$; $\eta_p = 0.34$) and return ($F_{1, 48} = 11.7$; $p < 0.01$; $\eta_p = 0.$) movements. Moreover, movement context did not affect COP peak velocity. Across groups and context conditions, COP peak velocity was faster during reaching to lateral than forward target ($F_{1, 48} = 13.8$; $p < 0.01$; $\eta_p = 0.26$), but was comparable between directions when returning to an upright position.

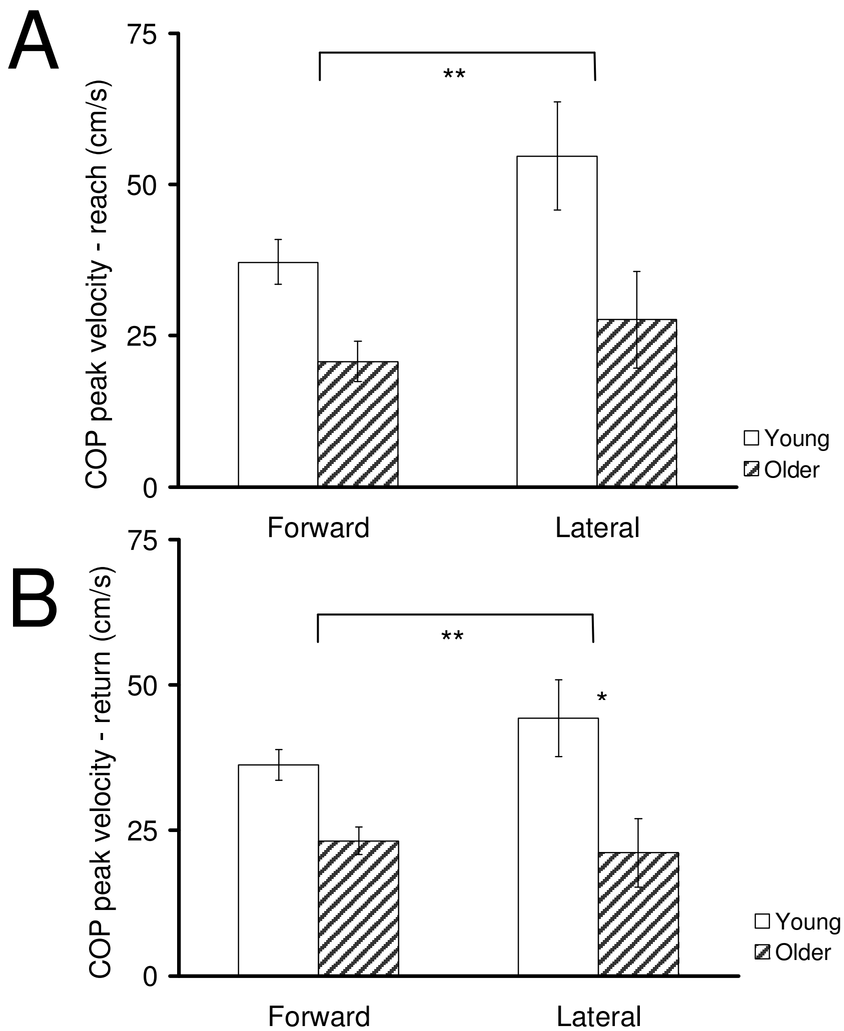

Figure 4.4 – Mean (±SE) COP peak velocity during reach (A) and return (B) movements in young and older adults. Data collapsed across point and grasp conditions. * p<0.05. ** p<0.01.

Primary variable: Center of pressure trajectory linearity

During reaching, COP trajectory linearity was not significantly affected by the effects of age, movement context, or target direction (Figure 4.5 A). During the return phase of the movement, COP trajectory linearity was significantly reduced in older adults in the grasping compared to the pointing condition, regardless of target directions (Figure 4.5 B). In contrast, movement context did not affect the COP trajectory linearity in young adults (effect of group and context: $F_{1, 49} = 5.7$; $p < 0.05$; $\eta_p = 0.16$; effect of group: $F_{1, 49} = 7.7$; $p < 0.05$; $\eta_p = 0.32$; effect of context: $F_{1, 49} = 9.9$; $p < 0.01$; $\eta_p = 0.25$). Across groups and context conditions, COP trajectory linearity was reduced when reaching in the forward compared to lateral targets ($F_{1, 49} = 5.6$; $p < 0.05$; $\eta_p = 0.34$).

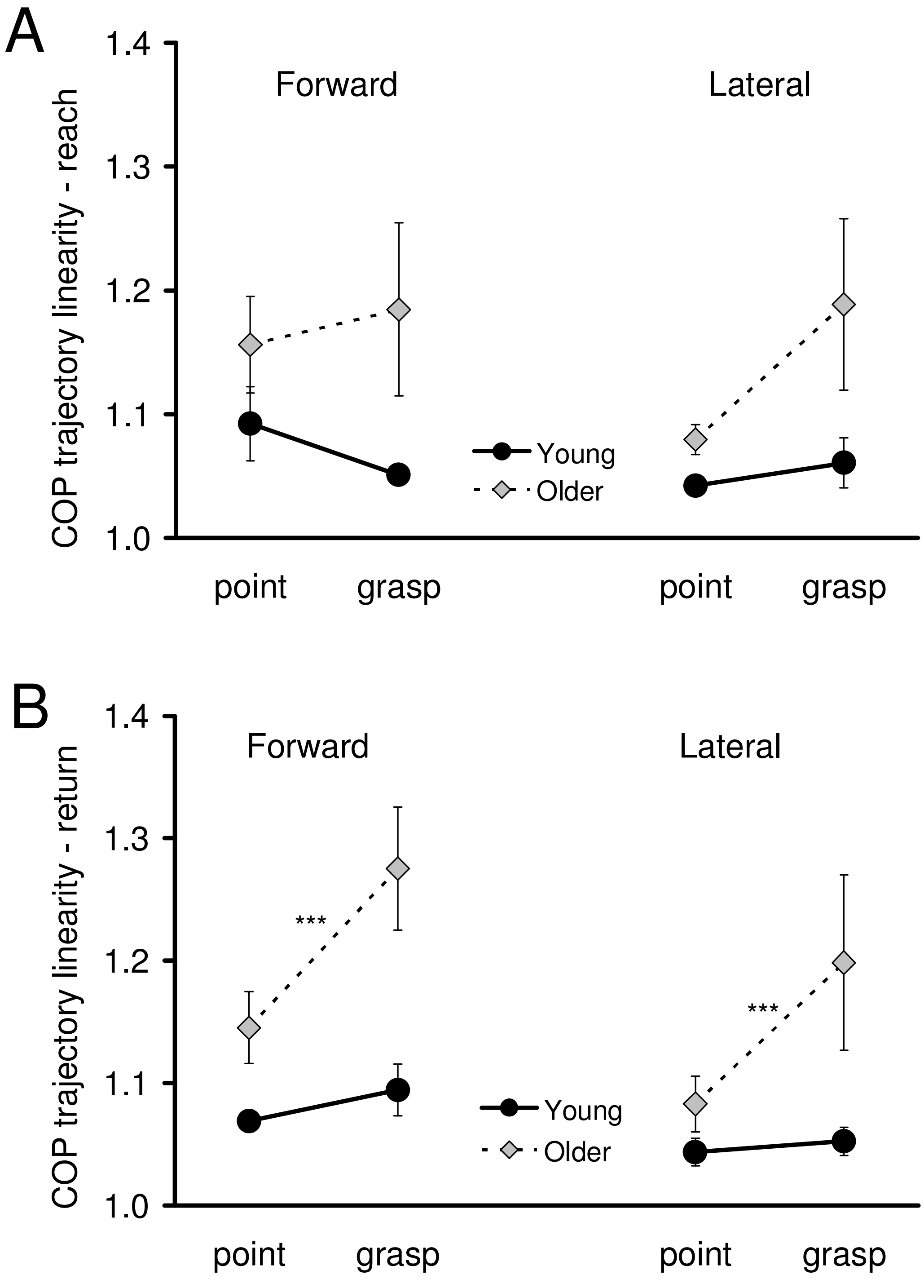

Figure 4.5 – Mean (±SE) COP trajectory linearity during reach (A) and return (B) movement cycle in young and older adults. *** $p<0.001$.

Secondary variables: Grasp Parameters

Older adults were able to generate comparable maximum grasp forces with similar grasp duration as young adults, regardless of the target direction (Table 4.2). Grasp force variability did not differ between groups. Across movement cycles, older adults were as consistent as young adults in generating maximum grasp forces at target acquisition. For both groups, grasp force variability was greater during reaching to the lateral than forward targets ($F_{1, 16} = 5.7$; $p < 0.05$; $\eta_p = 0.26$).

Table 4.2 – Grasp parameters in young and older adults.

	Young (mean ± S.E.)	Old (mean ± S.E.)
Grasp Forces (kg)		
Forward Target	1.7 ± 0.4	1.7 ± 0.4
Lateral Target	2.1 ± 0.4	1.9 ± 0.3
Grasp Force Variability (CV)		
Forward Target *	0.17 ± 0.03	0.16 ± 0.03
Lateral Target *	0.30 ± 0.04	0.21 ± 0.08
Grasp Duration (ms)		
Forward Target	331.4 ± 52.0	396.4 ± 58.6
Lateral Target	313.5 ± 39.0	377.4 ± 51.1

Differences between the forward and lateral targets were significant. * $p < 0.05$.

Secondary variable: Hand movement time

During the reach and return phases of the reaching task, hand movement time was not affected by the effect of group or movement context (Figure 4.6). For both young and older adults, return movements made from the lateral target took longer than returning movement made from the forward target ($F_{1, 49} = 16.0$; $p < 0.001$; $\eta_p = 0.42$).

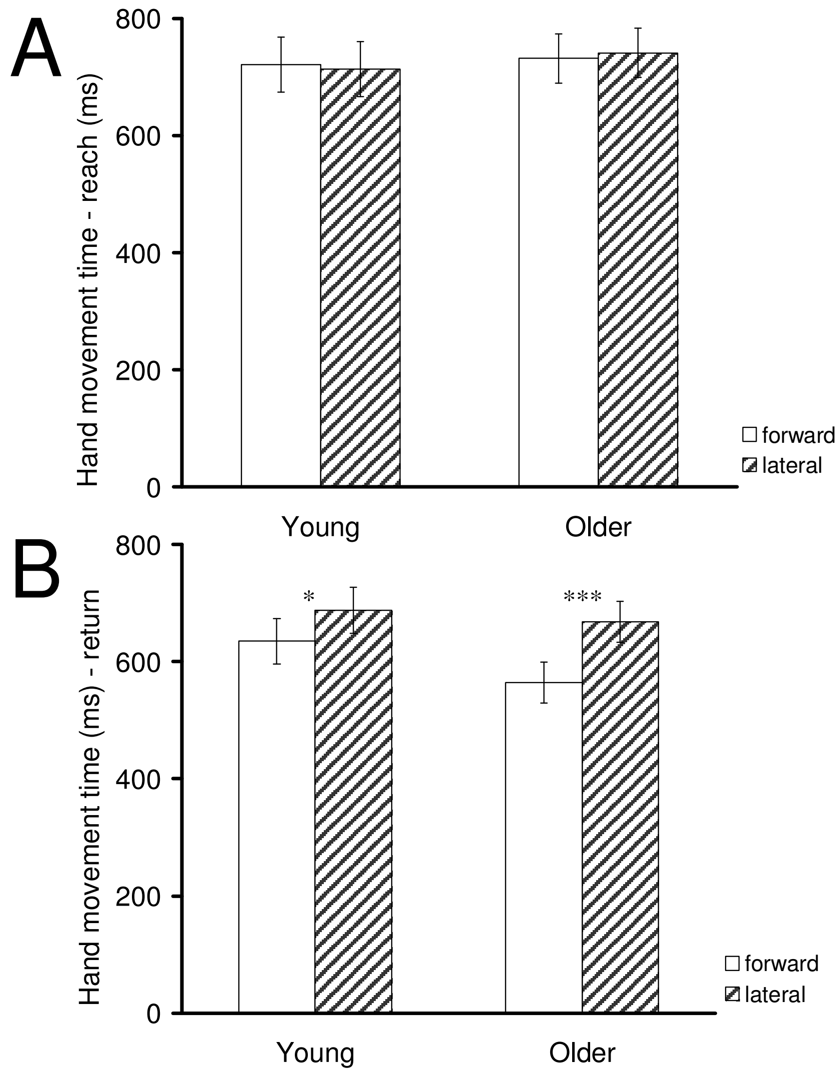

Figure 4.6 – Mean (±SE) hand movement time during reach (A) and return (B) phase in young and older adults. Data collapsed across grasp and point conditions. * p<0.05. * p<0.01.

Discussion

This study examined postural control in young and older adults during sequential reach and return movements performed from a standing position. The movement context was varied by the task goal at the end of the reach, i.e. pointing to versus grasping the target. It was found that COP trajectory linearity was reduced following grasping compared to pointing in older but not young adults. These results supported the primary hypothesis that postural control in older adults is affected by the movement context. As predicted in the secondary hypothesis, COP maximum displacement and peak velocity were reduced in older compared to young adults, regardless of the movement context and reach direction, reflecting an age-related reduction in stability limits. In accordance with the other secondary hypothesis, grasp duration, maximum grasp forces, and variability of maximum grasp forces across trials were comparable between groups, indicating that differences observed in postural control were unlikely due to altered grasp performance with age.

Center of pressure maximum displacement and peak velocity

In the present study, the target distance was equivalent to each subject's 90% of functional reach distance and was smaller in older compared to young adults. Consequently, smaller COP maximum displacements and peak velocities in older adults reflected an age-related reduction in stability limits, which have been shown in previous studies (Binda et al., 2003; King et al., 1994). Grasping versus pointing did not affect COP maximum displacement and peak velocity, indicating that the difficulty levels for maintaining balance were determined by the biomechanical constraint of target distance rather than the movement context. Moreover, age-related reduction in these COP variables did not vary between the forward versus lateral reach directions, suggesting that aging may affect the control of dynamic balance in the sagittal and frontal plane similarly.

For both age groups, COP peak velocity was faster while COP trajectory was straighter following grasping in the lateral compared to forward target condition. Without normalizing to the BOS dimension, COP maximum displacements were in fact, larger during the lateral compared forward reach. This could be due to different BOS dimensions in the AP and ML directions. Longer stance width compared to foot length allows for larger COP displacements in the ML than AP directions. Moreover, muscle synergies involved in the control of COP vary depending on the movement directions. The COP movements in the ML direction are primarily controlled by the activation of lateral muscles at the hips and trunk. On the other hand, muscles at both ankles and proximal legs and trunk are activated to shift the COP in the AP direction (Santos & Aruin, 2008; Winter et al., 1996). Current findings indicate that lateral loading and unloading responses produced by the proximal hip and trunk muscles may be more proficient in shifting the COP faster, over longer distances, and with straighter trajectories compared to the activation of distal ankle and proximal muscles.

<u>Effect of movement context on center of pressure trajectory: Primary hypothesis</u>

Prior to grasping, no age differences in COP trajectory linearity were observed. Maximum grasp forces and grasp duration were not different between young and older adults. Moreover, both groups consistently generated comparable maximum grasp forces across repetitive reach movement cycles. However, increased deviations in COP trajectory from a straight path during the return phase following grasping were observed in older but not young adults. Grasping at the end of the reach may have caused larger postural perturbations due to the requirement to generate grasp forces at target acquisition. In the standing position, grasp forces and associated postural adjustments are tightly coupled and planned in a feedforward mode according to the predicted perturbations induced by the grasp (Wing et al., 1997; Diermayr et al., 2008). Danion et al. (2007) found that in older adults, changes in grasp forces lagged changes in load forces, reflecting impaired feedforward control of grasp. Similarly, studies have reported age-related changes in anticipatory postural adjustments during arm movements (Bleuse et al., 2006; Inglis & Woollacott, 1988; Rogers et al., 1992; Woollacott & Manchester, 1993). The present study further demonstrates that older adults might have not been able to generate appropriate postural responses in anticipation of the perturbations associated with grasping. As a result, older adults experience increased postural instability following grasping from a standing position as reflected by reduced COP trajectory linearity during the return movement phase.

In addition to inadequate postural responses in anticipation of the grasp, older adults could have exploited the tactile feedback available during grasping to enhance postural stability. In quiet stance, light touch by finger contact with a stationary (Baccini et al., 2007; Jeka & Lackner, 1994; Jeka, 1997) or flexible surface (Johannsen et al., 2009; Lackner et al., 2001), and passive tactile feedback applied to the skin (Menz et al., 2006b; Rogers et al., 2001) have been found to reduce postural sway in young and older adults. The reduction in postural sway is not due to the mechanical support provided by the tactile surface/object since this light touch effect is reduced when peripheral sensation of the finger is blocked by tourniquet ischemia (Kouzaki & Masani, 2008). Further, light touch is more effective in reducing postural sway in older than young adults (Baccini et al., 2007). Therefore, tactile feedback arising from grasping could have improved postural stability to a greater extent in older adults. However, once tactile feedback was removed following the release of grasp, older adults might not have not been able to quickly reintegrate other sensory inputs in order to maintain postural stability. Indeed, it has been shown that older adults show a greater increase in postural sway in quiet stance when sensory inputs from visual, proprioceptive, or vestibular systems are removed or altered compared to young adults, reflecting an age-related declines in the processes of sensory integration (Bugnariu & Fung, 2007; Teasdale et al., 1991).

Implications

Current findings imply that the effect of movement context should not be overlooked in designing balance training programs for older adults. In daily activities, arm movements are frequently carried out with the goal of acquiring or manipulating objects, e.g. reaching to turn the door knob, pulling down blinds, hanging a coat, or picking up a pot. Movement context determines the forces involved and the sensory feedback available while one interacts with the object in the outside world and postural adjustments need to be planned appropriately for the circumstances defined by the movement context. A mismatch between the estimated and actual movement contexts could result in increased postural perturbations, loss of balance and/or failure to achieve the goal of a motor action. For instance, it can be predicted that older adults may be may be unable to turn the doorknob completely and/or experience unsteadiness if the turning forces produced do not match the actual resistance encountered. Therefore, it is imperative to integrate functional goals in the movements to enhance postural control.

While tactile feedback from contact with objects can be utilized to enhance postural control, withdrawing this type of somatosensory feedback may be detrimental to postural stability, particularly in older adults. Although healthy older subjects examined in the present study did not lose balance following removal of tactile feedback during the return movement phase, it is possible that frail older adults with balance problems may encounter more difficulties in maintaining postural stability under similar circumstances. Thus, balance training programs should incorporate the introduction and removal of sensory feedback by interacting with objects in the environment. This sensory component can be brought in during the course of movements to facilitate postural control in response to changes in sensory feedback.

Limitations

The small sample size in the present study may be considered a limitation that precludes generalization of current findings. In the present study, repeated measures design permitted each subject to serve as his/her own control and reduced the variability associated with individual differences. This approach allows for more economical and powerful analysis despite smaller than usual subject groups (Fitzmaurice et al., 2009). Moreover, practice effects of the task over repeated trials were minimized because the order of conditions was randomized across subjects. Based on current findings from the small group of healthy older adults, it is possible that age differences would have been more evident if a larger group of older subjects, including frail individuals, were tested.

Current grasping tasks required subjects to form an internal model associated with generating grasping forces at target acquisition. In the grasp and lift paradigm, multiple trials may be necessary before one can build an internal model of the frictional and inertial properties of the object to be picked up, particularly when picking up a novel object (Gordon et al., 1993). Thus, it is possible that older adults needed more practice trials to formulate an appropriate internal model for current grasping tasks. This adaptation process has been examined by Mallau and Simoneau (2008) using a grasp and lift paradigm performed by standing young and older subjects. Their results showed that across 30 trials, older adults continued to generate larger grasp force while young adults were able to reduce grasp force. Remarkably, older adults reduced postural sway after picking up the object to the same extent as young adults across trials. These results indicated that older adults prioritized the control of postural stability over repetitive trials because the consequences of falls are more significant than dropping the object being held. Similarly, in the present study, older adults might have focused more on stabilizing posture than modulating grasp forces across repetitive movement cycles. Moreover, no group differences in variability of maximum grasp forces across trials were observed, suggesting that the grasp performance in older adults reflected the control after adaptation.

Future Studies

The effect of tactile feedback on postural control in quiet stance has been examined extensively. In contrast, the exploitation of tactile feedback during dynamic balance tasks, as in the current experimental paradigms, has received little attention. Future studies are necessary to elucidate whether older adults can benefit from tactile feedback available during movement execution. For example, older adults can lean onto the cane for mechanical support during walking. It is not known to what extent older adults can benefit from the tactile feedback available while using the cane.

It has been shown that the estimate of a load to be lifted depends on prior experience with anticipatory postural adjustments becoming more appropriate for the load following repeated lifting movements (Toussaint et al., 1998). By introducing expected and unexpected loads over repetitive trials, it may be possible to elucidate the adaptation processes leading to the formation of an updated internal model for the forthcoming postural perturbations, particularly in older adults or other patient populations.

Conclusions

- The context of reaching movements, altered by pointing versus grasping a target at the end of the reach, influences postural control following interacting with the target in older but not young adults.
- The ability to plan feedforward postural adjustments according to the movement context is affected by age.

- When a movement context allows for the exploitation of tactile feedback, such as grasping the target, older adults may be likely to rely on this augmented sensory information to stabilize posture. Consequently, older adults experience increased postural instability once tactile feedback becomes unavailable, e.g. following release of the target.
- Balance training programs for older adults should not overlook the influence of movement context and tactile feedback pertaining to interacting with objects in the surrounding environment.

Chapter 5

General Discussion

Summary of Major Findings

The overall purpose of this dissertation was to explore the control of posture and movements during standing reach in young and older adults. In Chapter 2, age differences in anticipatory postural adjustments (APAs) and dynamic balance during movement execution were examined where reach heights were varied. In addition, whether reaching with the dominant and non-dominant hands would be associated with asymmetric postural control was investigated. It was shown that firstly, both young and older adults were able to modulate APAs with respect to changes in reach heights. Across all conditions, older adults produced larger APA amplitude despite comparable reach distance and slower hand mean velocity, reflecting an active over-control strategy to increase the safety margin for preventing loss of balance. Secondly, COP trajectory smoothness decreased in older adults during reaching to low targets and during returning from all target heights. Thus, dynamic balance represented by a smooth and controlled COP trajectory is affected by age, especially when voluntary movements involve shifting the COP backward and away from the anterior boundaries of the BOS. Furthermore, for both age groups, reaching with the dominant hand was associated with larger APA amplitude measured by the COP displacement and increased COP trajectory smoothness during movement execution. In older adults only, asymmetric APA amplitude measured by the axial torques were observed. Thus, parallel to asymmetric upper limb motor control, the organization of postural control may also be asymmetric.

Chapter 3 investigated whether the curvature of hand trajectory would be affected by age and target height in the workspace. In addition, the effect of reaching with the dominant versus the non-dominant hand on hand trajectory was examined. Whether the contribution of the trunk displacement in the reach would be different between groups was also explored. It was found that firstly, no age differences were found in the curvature of hand trajectory. For both age groups, hand trajectory was more curved during reaching to low compared to other higher targets. Therefore, curvature of hand trajectory during arm movements varies depending on the target location in three-dimensional workspace and is independent of age. Secondly, although current experimental tasks did not impose high accuracy constraints, hand movement time was longer when reaching with the non-dominant versus dominant hand but only in older adults. This supports the view that aging can lead to increased asymmetry in the control of upper limb movement performance. Moreover, forward trunk flexion during reaching to low targets was reduced with in older compared to young adults, reflecting an adaptive strategy to limit postural perturbations from moving a large mass of the trunk towards a target.

Chapter 4 investigated whether the movement context, varied by pointing to versus grasping a target would influence dynamic balance measured by COP trajectory linearity during sequential reach and return movements. It was found that in older adults only, COP trajectory linearity decreased under the grasping condition during the return movement. On the other hand, grasping forces and duration were comparable between groups, suggesting that altered dynamic balance was not due to inadequate grasp performance. Therefore, the control of dynamic balance based on the movement context of the reach is affected by age.

Models of Postural Control

Since Sherrington wrote about simple reflexes and the control of movement in 1906 (Sherrington, 1906), extensive research has been conducted to develop models for human motor control. In 1971, Nashner (1971) proposed a feedback based model of postural control in experiments that introduced unexpected external disturbances to the support surface. However, models of feedforward postural control have emerged only in recent decades (Cordo & Nashner, 1982; Massion, 1992). More recently, researchers have attempted to formulate a unified model for the control of postural and movement because most functional tasks involve the whole body and do not have easily distinguishable focal movement versus postural components (Berret et al., 2009).

<u>Internal Model</u>

One fundamental concept in current postural control models is the role played by the internal model that encodes postural orientation and stability. Baroni et al. (2001) developed such a model for postural control. An internal model of the body geometry and dynamics is formed based on visual, proprioceptive, and vestibular sensory feedback from prior motor experience. This internal model is used to plan feedforward postural responses and to estimate sensory feedback associated with the forthcoming movements. Sensory feedback related to the controlled variable is compared with the estimated sensory feedback related to the same variable, such as the position of the COG or the task goal of holding a full glass of water. Differences found from this comparison are used to correct postural stability and adapt the internal model so that it becomes compatible with the current task.

Ahmed and Ashton-Miller (2007) proposed a postural control model regarding how the central nervous system detects loss of balance using an internal model. Their model states that the central nervous system (CNS) sends the control input to the internal model and the motor system. This internal model is not the exact representation of the system. Instead, it calculates the predicted output based on the control input in real-time. The error signal, i.e. the difference between the predicted and actual output obtained from sensory feedback, is sent to a control error anomaly (CEA) detector. The CEA detector compares the error signal to a threshold set at three standard deviations over the mean of the baseline signal. Compensatory responses are initiated once the error signal exceeds the threshold, indicating a loss of balance. The authors demonstrated that during a maximum forward reach, the CNS does not necessarily have to use all control errors. For instance, the control error of leg acceleration resulted in a greater success in detecting a loss of balance than the control error of head acceleration.

Taken together, the above two postural control models demonstrate the importance of the internal model. The control of postural stability may be largely depend on whether the internal model provides an accurate estimate of the outcome from the central command. Moreover, deviations from this prediction are used to update the internal model for planning of future postural responses.

Central Set

According to Massion (1992), the performance and efficiency of a postural task is influenced by the central set, defined as a state in which transmission parameters in various sensorimotor pathways have been adjusted to suit the initial task context (Prochazka, 1989). Recently, Jacobs and Horak (2007) suggested that cerebral cortex can modify the central set indirectly via the connections with cerebellum and basal ganglia. Cerebral cortex primes the postural response synergies assembled in the brainstem in order to optimize postural responses for a given task context. This central set is in part, determined from prior experience. For example, when standing subjects pick up an object of the same load repetitively, APAs become gradually scaled to the expected amplitude of the load (Toussaint et al., 1998). Other factors, such as cognitive state, initial sensory-motor conditions, or instruction, all represent adjustments in central set (Jacobs & Horak, 2007).

Movement Context

Interestingly, the concept of central set in postural control may be comparable to the view of the estimation of "movement context" in the control of motor behaviors (Vetter & Wolpert, 2000). Vetter and Wolpert (2000) defined movement context as the parameters of the motor system and the prevailing conditions in the environment (e.g. the characteristics of objects to be acquired). They argued that successful performance of a task depends on whether the motor commands match the estimated context. In this connection, both central setting for postural control and matching of movement context during voluntary movements can optimize the performance level.

Aging Differences in Postural Control

Altered Internal Model and Central Set for Postural Control in Older Adults

As suggested by Baroni et al. (2001), appropriate programming of feedforward postural responses is largely determined by the function of the internal model, which is formulated based on sensory feedback and adapted by prior experience. With age-related declines in the quality of peripheral sensation (Era et al., 1996; Lord et al., 1991), visual (Era et al., 1996; Lord et al., 1991), and vestibular inputs (Kristinsdottir et al., 2001), this internal model can be altered. Horak (1989) has suggested that an altered internal representation of stability limits leads older adults to use inappropriate hip strategy for correcting balance even when the postural perturbation is small and can be corrected with ankle strategy. Moreover, factors representing changes in the central set, such as fear of falling (Binda et al., 2003) and altered perception of one's stability limits (Robinovitch & Cronin, 1999), may cause older adults to avoid moving the COP towards their maximum capacity. Consequently, the adaptability of the internal model may be affected due to a lack of sufficient experience with a movement disturbance that shifts the COP towards the boundaries of the stability limits.

There is also evidence showing that altered central set may cause older adults to select a postural response by "default". Mille et al. (2003) found that following unexpected disturbance to upright stance, older adults more likely step to regain balance compared to young adults. This age-related increase in the frequency of stepping is not correlated with reaction time, peripheral sensation, or plantarflexor strength and rate of torque production, and hence, can not be directly attributed to declines in sensorimotor and musculoskeletal function. They concluded that in older adults, stepping may be a pre-selected postural response triggered by the event of perturbation.

Overall, older adults may present inadequate postural responses due to age-related changes in the internal model and central setting for postural control.

Current Findings Related to Postural Control Model

APAs are generally scaled according to the expected disturbance generated from the limb movement. However, results from Chapter 2 showed that older adults generated larger APA amplitude even though they did not produce faster or larger reaching movements. These age differences may reflect an active over-control strategy to increase the safety margin for preventing loss of balance. It is possible that with age, the internal model becomes less efficient and accurate in predicting the mechanical effects between active muscles forces, passive effects from reaction forces, gravitational forces, and other external forces arising from the objects in the environment. Thus, older adults resort to using greater active control by generating larger APAs to minimize the effects of other passive and less predictable forces. Moreover, a less adaptive internal model may cause older adults to change the central set for selecting postural responses. Thus, older adults might have, “by default,” increased the output for generating APAs.

The impact of central set on postural control can be more directly assessed by changing the movement context. This was examined in Chapter 4 by altering the manipulation component required at the end of the reach movement. Current findings of age differences in COP trajectory linearity during the return movement phase between the grasping and pointing conditions indicate that movement context of the reach affects dynamic balance in older adults. Adding a grasping component at the end of the reach necessitates the subjects to estimate the disturbance associated with exerting grasping forces. In addition, during grasping, the COP is maintained close to the anterior boundaries of the BOS for a longer duration in order to complete the grasp component, which, in turn, presents a greater challenge for postural control. In the present study, older adults might not have been able to accurately estimate the disturbance related to grasping based on the internal model and program APA accordingly. In addition, under the grasping conditions, the central setting might have pre-selected a strategy to utilize tactile feedback available during grasping to enhance postural stability. Since aging affects the processes of sensory integration (Bugnariu & Fung, 2007; Teasdale et al., 1991), changes in sensory inputs following the removal of tactile feedback during the returning movement phase may have a far greater impact on postural stability for older compared to young adults.

Dynamic Balance during Movement Execution

Measures of COP Trajectory for Dynamic Balance

The center of pressure (COP) corresponds to the location of the ground reaction force vector on the BOS. It reflects the net results of postural muscle activity in order to keep the position of center of gravity (COG) within the BOS (Winter, 1990). In quiet stance, measures of the variability in COP trajectory (e.g. standard deviation, root mean square, average velocity or amplitudes of COP trajectories) have been developed to assess postural stability (Lee et al., 2009; Rougier, 2008). These measures have been used to identify older adults with impaired balance or at risks of falls (Brauer et al., 2000; Kim et al., 2008; Piirtola & Era, 2006; Raymakers et al., 2005; Teasdale et al., 1991). During the performance of voluntary movements, COP displacement amplitude or velocity is the most commonly used measures for describing dynamic balance (King et al., 1994; Garland et al., 1997; Holbein-Jenny et al., 2007). Nevertheless, the redundancy of the motor system predicts that different synergies or muscle activation patterns can shift the COP to a similar extent. For example, during arm raising movement, Kanekar et al. (2008) observed that exercise-induced fatigue of postural and prime mover muscles did not change the COP displacement amplitude although the muscle activity was altered. Therefore, measures of COP maximum displacement or velocity may be inadequate in examining dynamic balance.

Results from this dissertation demonstrated that COP trajectory smoothness (Chapter 2) and linearity (Chapter 4) rather than COP maximum displacement may be more sensitive measures to distinguish age differences in dynamic balance. Moreover, recent studies have also shown that COP trajectory smoothness was increased in older adults following balance training with Tai Chi (Hass et al., 2004), and decreased in elderly patients with Parkinson's disease compared to healthy older adults (Hass et al., 2008). Therefore, measures describing the spatial-temporal characteristics of COP trajectories, i.e. dynamic postural sway, may provide more insights into dynamic balance control.

Difficulties in Controlling Backward COP Displacement in Older Adults

This dissertation showed that older adults may encounter more difficulties in shifting the COP in the backward direction, i.e. away from the anterior towards the posterior boundaries of the BOS (Chapter 2). In upright stance, anterior muscles (tibialis anterior, rectus femoris, rectus abdominis) shift the COP backwards whereas posterior muscles (soleus, biceps femoris, erector spinae) shift the COP forward (Krishnamoorthy et al., 2003; Krishnamoorthy & Latash, 2005). Declines in COP trajectory smoothness and linearity associated with return movements in older adults may be due to a reduction in leg muscle strength with age (Endo et al., 2002; Goodpaster et al., 2006; Thelen et al., 1996; Winegard et al., 1996), although there is no evidence to suggest that this reduction is greater in anterior rather than posterior leg muscles. However, it is well known that aging preferentially affects fast twitch fibers (Lexell, 1995), which constitute a greater percentage of muscle fibers in anterior tibialis and rectus femoris compared to, for example, soleus and biceps femoris (Monster et al., 1978). Thus, in older adults, difficulties in controlling COP backward movements may be related to different rates of declines in the anterior compared to posterior leg muscle strength.

Moreover, difficulties in shifting the COP backward in older adults may be due to the characteristics of stability limits in the forefoot area compared to the region closer to the heel. Chou et al. (2009) found that the great toe plays an important function is maintaining standing balance. By keeping the great toe from contact with the BOS, postural sway in quiet stance was increased and the ability to shift the COP was reduced compared to normal foot position. Therefore, shifting the COP forward may have a greater advantage of using the big toe to stabilize posture compared to shifting the COP backward with decreased weight bearing on the great toes.

In addition, reaching to a target might have provided a visual anchor because subjects gazed at the target in order to acquire it. However, during the return movement, this visual anchor was no longer available since subjects already acquired the target. Changing a visual anchor, such as introducing a scene of door opening, can increase postural sway during quiet stance in older compared to young adults (Simoneau et al., 1999). Therefore, in this dissertation, removing the visual anchoring on the target could have a greater impact on postural control for older adults.

Coordination of Arm Movements with Posture

Influence of Trunk Displacement on Hand Trajectory

Relatively straight hand trajectories are viewed as a constraint for motor control by the CNS (Morasso, 1981; Soechting & Lacquaniti, 1981), and are commonly used as the criteria in various models proposed for planning and executing arm movements in a three-dimensional world (Biess et al., 2007; Gielen, 2009). Results from this dissertation (Chapter 3) demonstrated that hand trajectories are more curved when the trunk contributes substantially to moving the hand towards the target during a reaching task. Similarly, Pigeon et al. (2003b) found that during arm movements performed in a horizontal plane, the curvature of hand trajectories was increased as the amount of trunk rotation was increased. However, they also found that this effect was independent of movement speed, indicating that the deviation from a straight hand trajectory was not related to the dynamics of the task. Flash (1987) proposed that deviations of hand trajectories from a straight path arise from the effects of the inertial and viscous-elastic characteristics of the moving segments. Based on Flash's model of motor control (1987), increased curvature of hand trajectories reflects the difficulties in implementing the parameters for a straight path due to moving a large mass, e.g. the trunk.

Adaptive Strategy in Coordination of Arm and Posture in Older Adults

Arm movements performed from a standing position require the coordination of whole body segments and the control of postural stability. According to Massion (1992, 1994, 2004), the central organization for these types of tasks involves a parallel control system: one for movement and the other for posture. Recently, studies with principal component analysis (a regression method to identify variables that covary) have found that joint coupling patterns fall into two primary functional groups during whole body reaching tasks. One mainly controls hand trajectory to meet the movement goal while the other coordinates lower extremities, trunk, and head to maintain postural stability (Kaminski, 2006; Berret et al., 2009).

Current results showed that postural control was influenced by age (Chapter 2 & 4) while the straightness of hand trajectories was relatively comparable between groups (Chapter 3 & 4). Although older adults preserved straight hand trajectories during reaching from standing, they did so with a reduction in the amount of trunk flexion. This strategy minimized postural perturbations arising from moving a large mass, i.e. the trunk. Moreover, it reduced the demands for controlling multiple joints and integrating sensory inputs associated with moving the trunk. In older adults, the trunk movements could also be limited due to the requirement to generate muscle torques across multiple joints simultaneously. Therefore, during the performance of whole body movement tasks, aging affects the postural control component while the movement goal is achieved by adaptive kinematic strategies.

To further elucidate the coordination of posture and movement, regression analysis of movement peak velocities and APA amplitude was performed for data presented in Chapter 2 and 3 (Appendix D and E). It was found that for both young and older adults, hand and trunk peak velocities were significantly correlated with APA amplitude measured by the COP displacements. Larger hand peak velocities were associated with smaller APA amplitude whereas larger trunk peak velocities were associated with larger APA amplitude. These findings are likely due to differences in the contribution of the arm and the trunk segment and the APA amplitude across different target heights. In current experimental tasks, reaching to low target was accomplished primarily with the trunk displacement and with larger APA amplitude whereas reaching to higher targets required mostly arm movements and with smaller APA amplitude. Moreover, the correlation relationships between trunk velocities and APA amplitude were significantly difference between groups. For older adults, each incremental change in APA amplitude caused a smaller incremental change in trunk peak velocities compared to young adults. The results confirmed that older adults generated larger APAs without making a faster movement.

Asymmetric Postural Control Associated with Handedness

It has been suggested that arm movements made by the dominant versus non-dominant hand involves different control processes. The dominant arm system is more proficient in feedforward control of intersegmental dynamics whereas the non-dominant arm system is superior in feedback-based control during the later phase of movement execution (Bagesteiro & Sainburg, 2002; Sainburg, 2002; Sainburg & Kalakanis, 2000; Wang & Sainburg, 2005). Based on this dynamic dominance hypothesis (Sainburg, 2005), it can be predicted that APAs associated with dominant arm movements are more effective in counteracting the forthcoming reaction forces and generating appropriate neuromuscular responses to stabilize posture. Indeed, findings from this dissertation showed that, when reaching with the dominant compared to the non-dominant hand (Chapter 2), APA amplitude and duration were associated with smoother COP trajectory. This is the first known study to demonstrate that postural asymmetries exist in both the preparatory and dynamic aspects of postural control.

Whether aging leads to increased or decreased asymmetry in bilateral hemispheric function is still inconclusive. Current results are consistent with the right hemi-aging model, which predicts that there are greater declines in the right hemisphere with age (Brown & Jaffe, 1975). Indeed, asymmetric hand movement time (Chapter 3) and APA amplitudes measured by axial torque (Chapter 2) were observed in older but not young adults. Previous studies found that age-related increase in asymmetric upper limb motor performance is most evident during tasks with higher demands of precision, attention, and visual tracking, such as sequential drawing (Teixeira, 2008), aiming and line tracing (Francis & Spirduso, 2000; Kalisch et al., 2006), and Purdue Pegboard tasks (Francis & Spirduso, 2000; Weller & Latimer-Sayer, 1985). The experimental task in Chapter 2 and 3 involved the acquisition of a target using a whole hand grasp, which did not impose high accuracy constraints. Thus, current results indicate that aging is associated with increased asymmetric control of movements and posture even during the performance of familiar, functional reaching tasks without high precision demands.

Clinical Implications

This dissertation demonstrates that older adults generate larger APA amplitude to increase the safety margin for postural stability. This active “over-control” may be a strategy to minimize the passive and less predictable mechanical effects associated with reaching from standing, such as reaction forces. However, the ability to exploit these passive mechanical effects has been observed in young adults (Vernazza-Martin et al., 2008) and in older adults with improved postural stability after balance training (Forrest, 1997). Since APAs are mostly acquired based on previous experience with a movement disturbance (Massion et al., 1998; Toussaint et al., 1998), balance training programs should provide sufficient repetitions involving internally-generated perturbations such as reaching at different speeds to various workspace locations. In addition, older adults may have more difficulties in controlling COP trajectories during downward and backward directed movements. Therefore, balance training programs should not overlook the directional differences in the control of postural stability. Older adults may benefit from posterior and downward-oriented exercises, such as bending over, leaning or stepping backwards.

Whole body movement tasks involving the trunk (e.g. reaching to low targets) present greater challenges to postural and limb motor control. Limiting trunk displacements during movement execution may be an adaptive strategy with aging, which can reduce the complexity of multi-joint coordination and the maintenance of postural stability. Restraining the trunk during the training of arm movements as suggested by Michaelsen et al. (2006), however, could further reinforce the disuse of the trunk and thus may not be an effective strategy aimed at improving limb-posture control. Thus, instead of training the upper limb in a supported position, the trunk control should be introduced at some point in the rehabilitation program.

The influence of movement context on postural control in older adults should not be overlooked. Clinical balance assessment and training programs need to integrate various functional goals and movement context in the postural tasks. For instance, reaching movements are typically goal-directed towards objects in the surrounding environment. These functional elements are not present in, for example, the Functional Reach test which is commonly used to assess dynamic postural control (Duncan et al., 1990). The introduction of a manipulation component or interacting with objects at the end of the reach may present greater challenges to postural control for older adults, particularly when the manipulation involves novel or less predictable dynamics (e.g. pushing or picking up an unknown weight). Moreover, it is possible that tactile feedback available while one interacts with objects enhances postural stability. However, older adults may encounter increased postural instability following the removal of the sensory feedback. Therefore, balance training should also include changes in sensory feedback available in the tasks, such as provision and removal of tactile feedback during movement execution.

Limitations

In this dissertation, subjects were instructed to perform the task "as fast and accurately as possible" versus moving at their own preferred speed. This raises the question whether each subject weighed "speed" and "accuracy" equally during the performance. In the grasping condition (Chapter 2, 3, & 4), the accuracy constraint referred to successfully acquiring a relatively large target using a whole hand grasp. Thus, accuracy in this task approximated that required in many functional activities of daily living. In no case, did any subject "miss" the target. Similarly, in the pointing condition (Chapter 4), subjects were required to aim at the central region of the target (2.54 cm by 2.54 cm) although aiming accuracy was not emphasized nor measured during the performance. Again, none of the subjects was required to repeat the pointing task because of aiming errors. Overall, the experimental tasks employed in this dissertation were relatively simple and without high precision demands. Therefore, it was unlikely that subjects slowed down or changed their motor planning processes to meet the task constraint of accuracy.

In Chapter 2 and 3, whether the task presented challenges at a comparable level of each individual's maximum capacity of postural control is not known. The targets were placed at 110% of arm's length away and at three different heights, top of the head, shoulder's height, and 40% of body height. This method normalized the target locations and consequently, the biomechanical constraints of the tasks across subjects. Because aging is associated with a reduction in maximum reach distance (Duncan et al., 1992; Holbein-Jenny et al., 2007; Weiner et al., 1992), equivalent target locations could actually be more difficult for older compared to young adults. However, individuals normally function in the environment that is not normalized to each person's maximum capacity unless special designs have been implemented. For example, light switches, doorknobs, sink height, curb steps, and shelving at grocery stores do not have adjustable settings for individuals with different functional capacity or body dimensions. Therefore, the first part of this dissertation (Chapter 2 & 3) still provides valid analysis in the context that reflects the prevailing environmental conditions during daily activities. In Chapter 4, targets were positioned at each subject's 90% functional reach distance and hence, presented challenges equivalent to individual's maximum capacity. Overall, this dissertation revealed age differences in postural control, regardless whether the target was positioned according to the anthropometric measures or individual's maximum capacity.

During daily activities, individuals do not necessarily have to perform functional tasks at maximum speeds. Experimental tasks in this dissertation required subjects to make movements quickly but accurately. Whether the present results can be generalized to self-paced movements is not known although it has been shown that APA amplitude and duration are scaled with speeds (Horak et al., 1984, Lee et al., 1987), magnitudes (Kaminski & Simpkins, 2001; Mochizuki et al., 2004), and inertial loads (Bouisset et al., 2000; Horak et al., 1984) of the forthcoming movements. Thus, examining movements made at faster speeds provides insight into the maximum capacity of the postural and motor control systems. Moreover, studies have found that older adults most commonly attributed their falls to "hurrying too much" (Berg et al., 1997). Thus, examining postural control during movements performed at faster speeds may help to elucidate the mechanisms most likely contributing to loss of balance or falls.

In current experiments, subjects were tested in one session only and so it is possible that measures of postural stability and arm movement performance may not reflect performance during a second testing session. However, since data were obtained from several trials, within subject variability was minimized. To what extent limb-posture performance may change across multiple testing sessions remains to be determined. The review of current literature in this field indicated that data had been obtained in a single testing session.

Data collected in this dissertation were analyzed by the investigator. There may be concerns of bias in data processing and statistical analysis. However, all data were processed using custom-written programs using the same algorithms while statistical analysis was conducted with a professional statistician at the University of Michigan, and thus, controlled for bias. It is standard procedure in the Motor Control Laboratory that all students are responsible for analyzing their own data.

Future Studies

Older adults recruited in this dissertation were without diabetic, neurological, or debilitating musculoskeletal conditions and lived in the community independently. Functional balance tests revealed that their scores were within the general population norms reported by previous research. Studies recruiting older adults with impaired balance or different diseases may identify the mechanisms affecting the control of posture and movements. For instance, examining individuals with Parkinson's disease may help to elucidate the role of the cortico-basal ganglia loop in pre-selecting and optimizing postural responses based on current movement context. Moreover, studying patients with cerebellar lesions may reveal the role of the cortico-cerebellar loop in adapting postural responses based on prior experience (Jacobs & Horak, 2007).

In addition, clinical studies using double blinded, randomized control trials with various patient populations will further expand findings from this dissertation. More specifically, the effects of balance training programs can be investigated from the perspectives of whether the intervention can lead to changes in APAs and dynamic balance, whether using a functional task with different goals and movement context facilitate the learning processes of balance performance, and whether training strategies focusing on a stable and controlled COP trajectory during movement execution would be more effective.

Recently, principal component analysis to identify primary component or module, e.g. joint coupling and muscle recruitment patterns, has gained increasing attention in the studies of whole body movements. In whole body movement tasks, it is recognized that the CNS assembles two primary components. One contributes to achieving the movement goal and the other controls postural stability (Kaminski, 2006; Berret et al, 2009). Further studies are needed to examine whether aging affects these components for movement and postural control differently during whole body movement tasks.

Previous research has mostly examined spatial-temporal characteristics of COP trajectory in quiet stance but not during movement execution. Current results demonstrated that measures describing spatial-temporal characteristics of COP trajectory, such as smoothness (normalized jerk scores) and linearity, more significantly distinguished age differences in postural control. In contrast, measures of the extent of COP trajectory, i.e. maximum displacement, did not reveal differences between groups.

Future research is needed to develop valid and reliable COP measures of dynamic balance control. Furthermore, control processes contributing to different spatial-temporal characteristics of COP trajectories need to be identified. For instance, it remains to be examined whether smoothness and linearity of COP trajectory are related to the joint coupling and postural muscle recruitment patterns.

Chapter 6

Conclusions

- During standing reach to various heights in the workspace, older adults generate larger APA amplitude measured by the COP displacement, reflecting an active "over-control" strategy to increase the safety margin for postural stability, instead of exploiting passive mechanical effects.
- Older adults encounter more difficulties in controlling postural stability as reflected by a reduction in COP trajectory smoothness during backward- and downward-oriented movements.
- Hand trajectories in three-dimensional space are more curved during movements involving substantial displacement of the trunk, which present greater challenges in multi-joint coordination and postural stabilization particularly for older adults.
- Older adults show more asymmetric APA measured by axial torque and more asymmetric hand movement time during standing reach with the dominant versus non-dominant arm, suggesting that aging is associated with increased asymmetries in motor and postural control associated with upper limbs.
- Movement context altered by pointing versus grasping at the end of the reach affects postural control in older but not young adults.

Appendices

Appendix A

Telephone Screening Form

Date: ______________________________	Birth date Age: ________
Name: ______________________________	Male Female
Address: ______________________________	Right Handed Left Handed
______________________________	Ht: ____ Wt: ____
Phone: ______________________________	BMI: _______

In general would you say your health is: Excellent Very Good Good Fair

Yes No

☐ ☐ Do you participate in a competitive sport?

☐ ☐ Do you have difficulty driving, watching TV or reading because of poor eyesight?

☐ ☐ Do you have hearing loss (requiring a hearing aid)? Can you hear normal conversational voice?

☐ ☐ Do you have dizziness, feelings of faintness, unsteadiness or loss of balance?

- How many falls in the past 12 months?__________

☐ ☐ Do you have any limitations of movement?

- Such as walking, climbing stairs, reaching, lifting, bending or carrying

☐ ☐ Do you have a frequent bone pain; joint muscle, or back pain?

- Weakness or loss of motion?
- Use of a cane, brace, or assistive device?
- Physical therapy in the past 3 months for leg, back, arm, or shoulder condition?
- Worsens with activity?

- (Daily pain rated 6/10) “Rate your pain on a scale of 0 to 10, with 1 indicating very little pain and 10 being the worst pain you have ever experienced.”

☐ ☐ Do you have numbness, tingling or loss of sensation in your arms, legs or feet?

☐ ☐ Do you regularly experience lower leg pain while walking?

☐ ☐ Do you have chest pains or pressure; tightness in your chest; or shortness of breath with very light activities (such as walking)

☐ ☐ Do you often have difficulty learning, remembering, or concentrating?

☐ ☐ Do you often feel sad or depressed?

☐ ☐ Do you have any other medical condition or health problem which may affect your ability to participate in this study?

<u>Do you or have you had any of the following conditions (circle)</u>:

Head injury

Stroke or mini stroke

Heart Attack or bypass

High blood pressure

Diabetes

Arthritis

Parkinson’s disease

Nerve Damage:

- Carpal tunnel
- peripheral neuropathy
- sciatica

Severe osteoporosis

Joint replacement

Fractures

Other

Include:

- ☐ Age between 18-30 OR 65 and older
- ☐ Right-handed
- ☐ BMI < 30
- ☐ No participation in competitive sport activity
- ☐ No significant vestibular, ophthalmologic neurological or musculoskeletal condition
- ☐ No cognitive impairment that affects comprehension of task instruction.

Appendix B

Edinburgh Handedness Inventory

Name: _______________ Age: ______ Gender: M F

Please indicate your preference in the use of hands in the following activities by a + in the appropriate column. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, put ++. If in any case you are really indifferent, put a + in both columns.

Some of the activities require both hands. In these cases, the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

	Left	Right
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking match (match)		
10. Opening box (lid)		
11. Which foot do you prefer to kick with?		
12. Which eye do you use when using only one eye?		

Appendix C

Values of Partial Eta Squared Reported in Previous Studies

1. Table of partial eta squared from Mayer et al. (2006)

Table 2. Adjusted mean, standard deviation (SD), and sertraline-placebo partial eta-squared at each follow-up visit on the CSDD, HDRS, and NPI-M scales

Means (SD)	Placebo $n = 20$	Drug $n = 24$	t-values and p-values	Partial eta-squared*
Depression on CSDD				
Week 3	16.0(4.3)	14.1(8.4)	1.59 $p = 0.121$	0.062
Week 6	16.5(6.2)	11.3(7.8)	2.81 $p = 0.008$*	0.172*
Week 9	15.8(5.2)	10.3(7.8)	3.16 $p = 0.003$*	0.208*
Week 12	14.9(5.5)	10.3(7.7)	2.56 $p = 0.015$*	0.147*
Depression on HDRS				
Week 3	20.9(4.8)	17.8(9.5)	1.86 $p = 0.074$	0.084
Week 6	19.3(7.1)	12.9(9.4)	2.71 $p = 0.010$*	0.162*
Week 9	19.8(6.2)	14.4(9.3)	2.37 $p = 0.023$*	0.128*
Week 12	17.3(6.8)	13.2(9.0)	1.69 $p = 0.103$	0.070
Depression on NPI-M				
Week 3	16.9(8.6)	16.3(15.2)	0.69 $p = 0.492$	0.012
Week 6	16.8(9.1)	13.0(14.7)	1.43 $p = 0.161$	0.051
Week 9	16.6(8.7)	12.1(14.3)	1.34 $p = 0.191$	0.045
Week 12	14.2(12.1)	10.8(14.1)	1.05 $p = 0.304$	0.028

*The coefficient is tested by testing the corresponding F test in the Repeated Measures Analysis of Covariance but the test was examined by using the asymptotic distribution of the coefficient itself. In all cases the tests gave similar results.

2. Table of partial eta squared from Britz et al. (2009)

Table 2
Summary of statistics from univariate analysis.

Variable	r^2	Parameter	B	Sig.	η^2
On.Ar	0.308	Intercept	184,368.696	0.000	0.185
		LogAge	−48,257.066	0.000	0.281
		Height	−76.138	0.744	0.001
		Weight	−347.343	0.006	0.087
		Sex = female	−10,073.903	0.021	0.064
On.Dm	0.236	Intercept	394.842	0.000	0.242
		LogAge	−66.251	0.000	0.184
		Height	−0.051	0.903	0.000
		Weight	−0.655	0.004	0.095
		Sex = female	−18.402	0.019	0.065
On.Cr	0.359	Intercept	0.687	0.000	0.542
		LogAge	0.082	0.000	0.299
		Height	0.000	0.332	0.011
		Weight	0.000	0.561	0.004
		Sex = female	−0.005	0.449	0.007

B represents the regression coefficient for each parameter and partial eta-squared (η^2) values represent the proportion of the total variance accounted for by each parameter.

Appendix D

Regression Analysis for Hand Peak Velocity with APA Amplitude

Aims: To examine age differences in the relationships between hand peak velocity (Chapter 3 results) and APA amplitude (Chapter 2 results).

Method: Hand peak velocity and APA amplitude measured by COP displacements from all trials in each subject were analyzed using Linear Mixed Model (SPSS version 16.0). Hand peak velocity was entered as the dependent variable. APA amplitude, group, and group by APA amplitude interaction effects were entered as the fixed factors. Trial was entered as the repeated factor. Subject was entered as the subject factor with covariant structure in compound symmetry matrix. Slopes and intercepts of correlation between hand peak velocity and APP amplitude in each subject were calculated using linear regression analysis (SPSS version 16.0).

Results: The effect of APA amplitude was significant, indicating that hand peak velocity was significantly correlated with APA amplitude. No other effects were found. In Table D, correlation coefficients were negative for both groups, indicating that larger hand peak velocities were associated with smaller APA amplitude.

Table D. Intercepts and slopes of regression line for hand peak velocity and APA amplitude in young and older adults.

Group / Parameters	Young Mean (S.E.)	Older Mean (S.E.)
Intercept	327.6 (12.7)	315.6 (10.2)
Slope	-15.6 (1.7)	-13.1 (1.3)

Appendix E

Regression Analysis for Trunk Peak Velocity with APA Amplitude

Aims: To examine age differences in the relationships between trunk peak velocity (Chapter 3 results) and APA amplitude (Chapter 2 results).

Method: Trunk peak velocity and APA amplitude measured by COP displacements from all trials in each subject were analyzed using Linear Mixed Model (SPSS version 16.0). Trunk peak velocity was entered as the dependent variable. APA amplitude, group, and group by APA amplitude interaction effects were entered as the fixed factors. Trial was entered as the repeated factor. Subject was entered as the subject factor with covariant structure in compound symmetry matrix. Slopes and intercepts of correlation between trunk peak velocity and APA amplitude in each subject were calculated using linear regression analysis (SPSS version 16.0).

Results: The effect of APA amplitude was significant, indicating that trunk peak velocity was significantly correlated with APA amplitude. The interaction effect of group by APA amplitude was significant. Thus, correlation relationships between trunk peak velocity and APA amplitude were different between groups. As shown in Table E, the mean slope of correlations was smaller in older compared to young adults, suggesting that older adults generated larger APA amplitude for the same increment of trunk peak velocity.

Table E. Intercepts and slopes of regression line for trunk peak velocity and APA amplitude in young and older adults.

Group / Parameters	Young Mean (S.E.)	Older Mean (S.E.)
Intercept	-11.3 (12.6)	-18.7 (14.5)
Slope	18.1 (2.1)	13.2 (1.2)

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