Coordination of turning when standing and walking in healthy older adults and persons with Parkinson's disease

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

It is difficult to think of any activity that does not require some degree of turning. Despite the prevalence of turning in daily activities and the challenge it poses to mobility-impaired individuals such as those with Parkinson's disease, there is far less known about the multi-segmental control of turning than the control of standing and straight walking especially in elderly individuals and patient populations.

The purpose of this thesis was to examine the coordination of body segment reorientation in healthy older adults and people with Parkinson's disease (PD) during on-the-spot turns when standing and turns initiated when walking. The coordination of body segments was examined for small and large magnitude turns in both populations. PD participants were examined when "off" and "on" dopamine-replacement medication to determine the effects of medication on multi-segmental coordination when turning. The effect of walking velocity on the multi-segmental coordination of turning also was examined in healthy elderly participants for three different walking velocities.

This research revealed differences in coordination patterns for standing versus walking turns and for healthy older adults versus persons with PD. Healthy older adults reorient their head, shoulder, and pelvis in unison, followed by mediolateral foot displacement, during standing turns. This coordination pattern was observed for both small and large turns. By contrast, turns initiated by healthy older adults while walking displayed a top-down temporal sequence similar to that reported for healthy young adults, i.e., the head turns first, followed by the

shoulder and pelvis, and finally mediolateral displacement of the foot. This is a robust behavior which was not affected by the magnitude of the turn or walking velocity.

PD participants ("off" and "on" medication) displayed temporal coordination patterns similar to age-matched healthy older adults for both standing and walking turns. However, PD participants ("off" and "on" medication) differed from healthy older adults with respect to the velocity and magnitude of reorientation of body segments, i.e., spatial parameters of coordination. The peak angular velocity of each body segment was significantly smaller for PD participants than the healthy older adults during both standing and walking turns; this was observed for both small and large magnitude turns. The magnitude of reorientation of each body segment was measured at the onset of mediolateral foot displacement; this measure revealed significantly smaller head and shoulder rotations for PD participants versus healthy older adults during standing turns, but not walking turns. Medication had no significant effect on the temporal or spatial parameters of body segment coordination during standing and walking turns. Medication increased the magnitude of head turn during the 90° standing turns; however, the magnitude of head turn remained smaller than that of healthy older adults.

Multi-segmental coordination patterns differ for turns performed when standing (on-the-spot turn) versus when walking. The temporal parameters of these coordination patterns are not influenced by the magnitude of the turn or the velocity of walking and remain intact in Parkinson's disease. Parkinson's disease modifies the spatial parameters of coordination;

reducing the velocity and early magnitude of reorientation of each body segment. These spatial parameters are not affected by dopaminergic medication.

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Dedication

To Keyan and Kimia, the joy and pride of my life.

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Chapter 1: General Introduction

1.1 Introduction

Falls are the leading cause of injury and accidental death among older adults (Macpherson et al., 2005). Thirty to forty percent of community dwelling elderly aged 65 years and over fall at least once per year (Tinetti at al., 1988; Lord et al., 1994). Incidence of falls increases with age (Lord et al., 1994). The consequences of falls and fall-related injuries in elderly represent a major public health concern. Fall-related injuries in elderly leave a considerable burden on the individual, family, and community. The growing ageing population underscores the importance of prevention of falls to promote healthy living in elderly.

Falls are also a common problem for individuals with Parkinson's disease (PD). In a retrospective study by Balash and colleagues (2005) 46% of individuals with PD in advanced stages of the disease reported that they had fallen at least once during the past year, and 33% reported they suffer from recurrent falls (2 or more falls per year). Given that elderly individuals underestimate the frequency of their falls (Cummings et al., 1988), the actual frequency of falls might be even higher than the percentage reported by Balash and colleagues. The frequency of injurious falls was also high in advanced stages of PD; with 10.6% of individuals with PD reporting they needed medical intervention for their fall-related injuries (Balash et al., 2005). Fall-induced injuries and fear of future falls limit the individual's mobility (Tinetti et al., 1994; Bloem et al., 2001). Immobility has its own negative physiological and psychological consequences that further diminish the quality of life of the faller.

The aforementioned emphasizes the importance of prevention of falls and fall-related injuries in healthy elderly and individuals with PD. Essential to the prevention of falls is identifying and subsequently removing the factors that contribute to the falls. While trips and slips are responsible for falls in young and elderly, many of the falls among the elderly are the result of changing the direction of travel. Cumming and Klineberg (1994) showed that in healthy elderly falling while turning was 7.9 times more likely to cause a hip fracture than falling while walking straight ahead. In individuals with PD abnormal protective arm movements necessary to break the fall by an outstretched hand or by grabbing an external support (Carpenter et al., 2004) may further increase the incidence of a hip fracture in the event of a fall (Bloem et al., 2003). Report of difficulty turning is a sensitive predictor of the two key symptoms of PD locomotion: freezing and falling (Stack et al., 2006). This thesis provides insight to the potential cause of falls in healthy older adults and individuals with Parkinson's disease, i.e., a loss of coordination in reorientation of head, shoulder, pelvis, and feet during turning.

1.2 Movement characteristics of axial body rotation in healthy young adults

One of the major requirements of successful and safe locomotion is the ability to adapt the basic gait parameters to meet the environmental demands and the goal of locomotion (Patla, 1991). These adaptations are not simple variations of the basic gait patterns; rather, they require a complex reorganization of the normal gait pattern. The rate of success in adopting proper gait modifications to accommodate environmental demands and/or to achieve the locomotion goal depends on the magnitude of change required, the amount of time available,

the musculo-skeletal constraints, the type and velocity of locomotion, and the stability constraints (Patla, 1991).

Patla divided the adaptive gait strategies into two groups: avoidance strategies which include modifications of the gait patterns made to avoid stepping on a particular unsafe and/or undesirable surface; and accommodation strategies which include changes of the gait patterns made to accommodate changes of the walking surface that cannot be avoided, e.g. a slippery surface (Patla, 1991). Turning is an avoidance adaptive strategy since it is used to change the direction of travel to avoid bumping into obstacles. It is an important and fundamental component of steering which requires reorientation of the whole-body towards the new travel direction while continuing with the ongoing locomotion. Turning is a challenging component of locomotion that requires anticipatory postural adjustments (Xu et al., 2004), systematic reorientation of axial body segments towards the new direction of travel (Patla et al., 1999), and systematic modification of the basic gait parameters (i.e., asymmetric step length and ground reaction forces) (Orendurff et al., 2006; Courtine and Schieppati, 2003).

Since navigating around obstacles and changing travel direction are inevitable during activities of daily living, turning has a common occurrence in our everyday life. Different degrees of turns, initiated from a standing position or during walking, arise spontaneously during everyday activities such as making a cup of tea, or taking an item out of the refrigerator and bringing it to the dinner table.

Based on the strategies adopted for turning, Patla et al. (1999) classified turning into two major types: the step turn and the spin turn. The step turn involves change in the direction of

the travel path to the opposite side of the stance limb (i.e., going to the right with the right limb while the left foot is planted on the ground). The spin turn, however, involves change in the direction of the travel path towards the stance limb (i.e., going to the right with the left limb while the right foot is planted on the ground) (Patla et al., 1999).

In a series of experiments Patla and colleagues (1991) examined the turning strategies adopted by young healthy adults to change their walking direction. Participants were instructed to always initiate their turn with the same foot, but they were free to choose their new walking direction. Results of these studies indicated that participants showed a preference for the new walking direction. The preferred direction allowed the participants to proceed into the new direction by taking a step turn. In fact, when the available planning and execution time was limited (by postponing the turn signal), the step turn was the only strategy used by the limited number of participants who were able to turn successfully. Patla suggested that this preference was due to inherent advantages of the step turn over the spin turn. With step turn, the center of mass (COM) always remains within the base of support, therefore, stability is maintained. Furthermore, the step turn requires increasing the activity level of the already activated muscles, while the spin turn requires inhibiting one group of muscles and activating another group and increasing the magnitude of activity in these newly recruited muscles to an appropriate level (Patla et al., 1991). The authors concluded that the preferred direction of a turn is determined by stability and the biomechanical cost of the modulations required to achieve a safe adaptive gait pattern.

Recently, Taylor and colleagues (2005) compared the kinetic and kinematic characteristics of 90° spin and step turns of healthy young participants. Results of their study are in agreement with findings of the study conducted by Patla et al. (1991). Taylor et al. showed that spin turns impose a greater challenge to the locomotor system as they require increased range of motion in the transverse plane and greater muscular activity. During the spin turn, the COM trajectory falls outside the base of support for a significant duration of the stance phase. However, during the step turns, similar to the straight gait, COM remains within the base of support for almost the entire duration of the stance phase. This difference is due to the wider base of support during the step turns and the different characteristics of the two types of turns. Furthermore, the toe-to-toe distance, which is negatively related to the possibility of interference between the feet and the chance of tripping, is much greater during the step turn than during the spin turn. The authors concluded that in general biomechanics of the step turn are no more demanding than straight gait; therefore, they offer a safer and simpler strategy for turning towards a new direction than spin turns (Taylor et al., 2005).

Research has also shown that while turning, healthy young adults show a clear temporal sequence in initiation of rotation of different body segments (Patla et al., 1999). Patla and colleagues showed that in healthy young adults while changing the direction of the travel path, control of body COM in the medio-lateral plane precedes the reorientation of body segments into the new travel direction. Healthy young adults modify their foot placement and trunk roll motion to control and move their body COM towards the new direction of travel. This is followed by movements in the yaw plane which start from the head and proceed to the trunk and then to the foot in a top-down manner (Patla et al., 1999). This temporal

sequence in initiation of rotation of different body segments in the yaw plane is not related to a specific turning task; rather, similar top-down temporal sequences have been identified during online steering (Patla et al., 1999; Paquette et al., 2008), discrete on the spot turns (Hollands et al., 2004), continuous on the spot turns (Earhart and Hong, 2006), and podokinetic after-rotations (Earhart and Hong, 2006). However, the actual latencies reported in these studies are not consistent.

1.3 Age-related modifications of axial body rotation

Research has revealed age-related modifications in turning execution when turning is initiated during walking (Cao et al., 1997) or from a standing position (Meinhart-Shibata et al., 2005) even in healthy and physically active older adults. Cao and colleagues (1997) examined the performance of healthy young and elderly male and female participants during unexpected turns. Ten young males, ten young females, ten elderly males, and ten elderly females participated in this study. All participants were healthy and physically active. Participants were asked to walk along an 8 meter walkway and turn into one of the four exit paths incorporated on either side of the walkway at a 90° angle. Five poles were positioned on each side of the walkway to form four gates leading to the four exit paths. Lights, mounted on the poles, were used to signal the side and the location of the turn in each trial. The available response time (ART) was the time between the light signal and when the participant would have passed through the virtual wall created by the forward border of the designated gate had he/she continued to walk forward at his/her comfortable speed. Turning performance was examined with four different ARTs (375, 450, 600, and 750 ms), and the rate of success (RS) with each ART was recorded for each group of participants. A turn was

considered unsuccessful if: a) participant failed to arrest his/her body's forward momentum; b) participant hit the pole; c) participant stepped outside the lateral borders of the turn path; and d) the average speed of the turn was less than 70% of the participant's comfortable turning speed. The participants' comfortable turning speed was verified during comfortable turning trials in which participants were instructed about the location and direction of the turn before the trial began.

Results of this study showed that: 1) 99% of the failures across all participants and conditions were due to forward momentum arrest failure. 2) For each ART, young adults had significantly higher RS than healthy elderly. On average, older adults needed 112 ms additional ART to achieve the same RS as the young adults. 3) In both age groups and for every ART males had higher RS than females. This gender effect was greater among elderly than young adults (Cao et al., 1997). Further investigations revealed that older adults needed longer response time for successful turn mainly because it took them longer to begin decelerating their body COM. Older women also needed more time decelerating their body COM which contributed to their need for longer ART for performing a successful turn in comparison with older men (Cao et al., 1998).

Meinhart-Shibata and colleagues (2005) examined the turning strategies adopted by ten healthy young and ten healthy elderly women while performing a 180° on-the-spot turn. Participants were asked to pick up a light-weight bowl from a waist-high table in front of them, turn 180° in the indicated direction, and place the bowl on another table two meters behind their starting position. Participants were instructed to perform the task at their

comfortable speed as if they were preparing a meal in their own kitchen. Results of this study revealed differences between the two groups in the time and the number of steps taken to complete the turn, minimum foot separation distance, and the frequency of preparatory stepping strategy (i.e., taking a small first step in the direction of the turn by the contralateral foot). There was a trend for older women to turn slower, take more steps to complete the turn, and maintain greater distance between their feet during the turn than young women, although these differences did not reach significance. Furthermore, the older women used a preparatory stepping strategy more often than young women indicating a tendency by the older women to be more cautious when turning. The rotational velocity of the pelvis was smaller in elderly women, resulting in smaller angular momentum of the body that should be arrested at the end of the turn (Meinhart-Shibata et al., 2005). However, it remains unclear whether the reduced rotational velocity was an adopted strategy, or the result of age-related musculo-skeletal changes, or both.

Thigpen et al. (2000) examined the turning characteristics of young healthy adults, and older adults with and without turning difficulty. Participants were videotaped performing a self-paced 180° turn during the "Timed Up and Go" test. Movement characteristics of 180° turns were identified by careful observation of the recorded videotapes.

Results of this study showed that young healthy adults turn with a ballistic, discrete motion. All young adults used a pivot strategy to perform the turning task, completed the turn in less than 2.5 seconds, and took 2 or fewer steps while turning. Performance of the older adults without turning difficulty was more variable. Approximately half of the participants in this

group demonstrated turning characteristics similar to those of the young adults. However, the other half used more steps and took longer to complete the turn, showed occasional complete stops during the turn, and adopted a combination of partial pivoting on one foot and taking extra steps or weight shifts to complete the turn. Older adults with turning difficulty used multiple steps (5 or more) to achieve the turn, and showed marked hesitancy, pauses, and stops throughout the turn. Duration of the turn was significantly greater for these participants. Pivoting strategy was completely absent in performance of the older adults with turning difficulty. This group was the only one that demonstrated staggering during the turn. The authors suggested that modifications in turning characteristics of older adults especially those with turning difficulties might be due to their heavier reliance on feedback mechanisms during the turn. While healthy young adults were able to turn quickly using a discrete, ballistic movement, elderly participants used a series of steps to complete the turn. The multiple-step turn is a slower movement and allows the use of feedback information (Thigpen et al., 2000).

Fuller and colleagues (2007) investigated the characteristics of reorientation of body segments during turns embedded in locomotion in older adults. Thirteen older adults, 72-92 years old, were asked to walk at their self-selected pace along a 3m straight path and either continue to walk straight or turn off at an angle of 40° to either right or left and walk for an additional 2m. The direction of turn in each trial was specified before the trial began. Participants were instrumented with reflective markers and the walking trials were recorded by a video camera. Results showed that in older adults reorientation of body segments into the new direction of travel follows the same temporal sequence as in healthy young adults.

Older adults reorient their head towards the new travel direction through head yaw movements before reorienting their trunk. Results also showed that regardless of the direction of the turn, over two thirds of the elderly participants completed the turn over two steps. These "double step" turns were longer in duration than "single step" turns. The selection of a single or double step turn was not related to the performance of the participants in any of the functional mobility tests, e.g. Timed Up and Go test, Dynamic Gait Index, and 7m self-paced walking. However, older adults with lower balance confidence were significantly more likely to choose a double step turn to change the direction of their travel path (Fuller et al., 2007).

Crenna and colleagues examined the performance of fifteen healthy older adults (mean±std age=67.7±2.7) as they made a 90º step turn to their left in the middle of their walk. Kinematic data were recorded using multiple cameras (SMART, BTS, Italy). Results revealed that healthy elderly reorient their body towards the new direction of travel in a top-down sequence with head turn preceding the reorientation of the upper trunk by 220ms (Crenna et al., 2007). Similar top-down sequence of reorientation of body segments during turns embedded in locomotion in healthy elderly as they make a 90° step turn to their left are reported by Carpinella et al. (2007) and Ferrarin et al. (2006).

A recent study by Paquette et al. (2008) is the only study that has examined the sequence and timing of reorientation of different body segments in healthy young and older adults during both step and spin turns. Performance of six healthy young and six healthy elderly was examined as they made 40° turns to their right or left. The starting foot and less often the

start point were adjusted to require participants to perform two different types of turns: step and spin turns. The time of heel contact of the foot that was planted on the floor during the turn was considered as the reference time (time = 0). The onset of head yaw, trunk yaw, trunk roll, and medio-lateral foot displacement during the approach phase was calculated relative to the aforementioned reference time. Results revealed similar top-down sequence in reorientation of different body segments in young and older adults with no significant difference between young and elderly in the onset time of head yaw, trunk yaw, trunk roll and medio-lateral foot placement. More importantly, turn type had no significant main or interaction effect on the sequence and timing of segment reorientation (Paquette et al., 2008).

To the best of our knowledge the sequence and timing of body segment reorientation during on-the-spot turns has not been investigated in elderly population yet.

1.4 Deficits in axial body rotation in persons with Parkinson's disease

Parkinson's disease is the most common neurodegenerative disease after Alzheimer's disease, with a prevalence of 150/100 000 (Schapira, 1999). It is the most common basal ganglia degenerative disorder. In PD the progressive loss of dopaminergic neurons in the substantia nigra pars compacta reduces the inhibitory effects of striatonigral pathways on the internal globus pallidus. The aforementioned results in an abnormally higher inhibitory discharge from globus pallidus to the cortical motor areas and selected brain stem nuclei, which in turn produces specific motor symptoms (Kandel et al., 2000).

Impaired balance control and postural instability are among the main symptoms of PD (Kandel et al., 2000). Postural instability has a major effect on the quality of life of

individuals with PD since it increases the incidence of loss of balance and falls. Individuals with PD walk slower with smaller steps. The shuffling gait is accompanied by a stooped posture and reduced or absent arm swing. Ground clearance is also reduced which increases the risk of tripping (Martin, 1967). However, cadence remains within normal range (Blin et al., 1990; O'Sullivan et al., 1998). The steady rhythm of normal gait is impaired in PD; therefore, the gait of individuals with PD is more variable (Blin et al., 1991; Frenkel-Tolendo et al., 2005; Baltadjieva et al., 2006). Chastan and colleagues (2008) reported that individuals with PD could experience postural instability even in the early stages of the disease when this symptom is not easily detected by clinical examinations.

It is well-known that postural instability of individuals with PD is exaggerated in specific circumstances. For example, individuals with PD show poorer balance and greater incidence of falls while performing specific tasks such as turning (Giladi et al., 1992; Bloem et al., 2001). Freezing of gait is also common in advanced stages of PD. Freezing episodes are transient hesitation and blocks in the middle of motion. Giladi and colleagues reported that 45% of individuals with PD who experienced freezing, reported freezing while turning (Giladi et al., 1992). Stack and colleagues showed that the report of difficulty turning is a sensitive predictor of the two key symptoms of PD locomotion: freezing and falling (Stack et al., 2006). The association of turning with falls and freezing in individuals with PD highlights the importance of understanding the turning impairment in this patient population.

Vaugoyeau et al. (2003) examined performance of ten PD participants and five age-matched healthy controls while taking a diagonal step at 45° in two different conditions: a diagonal

step without changing the body orientation, and a diagonal step with body reorientation in the direction of step. All participants with PD were in advanced stages of the disease (stages III and IV of the Hoehn and Yahr scale) and had a history of previous falls. Participants with PD were tested while "on" dopaminergic medications. Results of their study showed that regardless of the condition, the duration of the postural phase (defined as the time between the first variation of the horizontal force in the sagittal plane and the first variation in the velocity of the marker positioned on the participant's malleolus) was significantly longer in PD participants than in controls. Furthermore, in both conditions, participants with PD took shorter steps and produced lower amplitudes of horizontal forces than their healthy counterparts. Results also showed that while performance of the healthy participants remained unchanged across conditions, postural performance of PD participants showed further decrements as the task complexity increased. Step length, step velocity, and the propulsive forces during stepping movements were all significantly reduced when PD participants performed the stepping task while simultaneously reorienting their body (Vaugoyeau et al., 2003). Based on these findings authors suggested that the poor performance of individuals with PD in taking a diagonal step is due to difficulty in coordinating the two different components of the task: the whole body inclination in forward direction, and body rotation in the direction of step.

Investigating the temporal organization of movements of different body segments in the yaw plane as participants took a diagonal step while simultaneously reorienting their body provided further insight into the source of poor performance of PD participants in this task. While taking a diagonal step with simultaneous body reorientation, healthy participants

initiated their body rotation with rotation of the head at the beginning of the postural phase followed by simultaneous rotation of the shoulders and pelvis. Furthermore, rotation of all three segments started before the postural phase ended, i.e., before the foot was lifted from the floor. PD participants, however, demonstrated a global delay in the onset of body rotation (Vaugoyeau et al., 2006). In PD participants, head rotation started long after the onset of the postural phase and was followed by rotation of the shoulders and finally the rotation of the pelvis. Unlike healthy controls, in PD participants there was a significant delay between the onset of rotation of shoulders and pelvis. The delay in the onset of pelvic rotation increased as the velocity of rotation increased indicating that this delay was not due to the general slowness of movements in PD participants (Vaugoyeau et al., 2006). Authors speculated that while the specific impairment of temporal organization of the axial rotation in PD participants may be related to a general role of the basal ganglia in orientation of the body in space, it could also reflect a major deficit in coordinating the descending or top-down control of body orientation starting from the head and acting on the shoulders with the ascending or bottom-up control of the pelvic orientation starting from the feet.

Turning difficulty in individuals with PD could be the result of the musculoskeletal impairments due to ageing (such as reduced flexibility of spine), and the neurological impairments that relate directly to PD (such as stiffness, tremor, impaired motor planning). The greater background activity in lower limbs and trunk muscles (Horak et al., 1996; Carpenter et al., 2004; Dimitrova et al., 2004), increased balance correcting responses in leg, trunk and arm muscles (Carpenter et al., 2004), and the co-contraction of the agonist and antagonist muscles (Horak et al., 1996; Dimitrova et al., 2004; Carpenter et al., 2004) result

in overall stiffness in individuals with PD. While the natural increase in joint and muscle stiffness with ageing makes turning difficult, increased stiffness due to neurological impairments further compromises turning ability of individuals with PD. Schenkman et al. (2000; 2001) evaluated the turning behavior of a group of PD participants (Hoehn and Yahr stages 1.5 to 3) and an age-matched healthy control group. Participants' spinal flexibility was measured using Functional Axial Rotation (FAR) test. FAR measures the participants' ability to turn and look at the wall behind them while sitting on a stool. FAR incorporates all spinal segments and is considered a measure of combined spinal flexibility. Results of these studies showed that spinal flexibility is reduced in PD participants to a greater extent than in their age-matched healthy counterparts. The greater reduction of spinal range of motion was evident even in early stages of the disease (Schenkman et al., 2000; 2001). Schenkman and colleagues also showed that spinal flexibility as measured by FAR is a significant predictor of supine-to-stand time and the number of steps taken during a 360° turn, which both were significantly greater in PD participants than healthy controls (Schenkman et al., 2000).

In individuals with PD, axial rigidity or reduced spinal flexibility may prevent proper uncoupling of the thoracic and pelvic rotation during locomotion. Van Emmerik and Wagenaar (1996) showed that in young healthy adults, movements of the thorax and pelvis in yaw plane are predominantly in phase at lower walking velocities. However, at higher walking velocities the thorax and pelvis are coordinated in a more out-of-phase mode. The uncoupling of the thoracic and pelvic rotation with increasing walking speed is likely an adaptive behavior to minimize the chance of instability by reducing the overall external moment acting on the trunk (Van Emmerik and Wagenaar, 1996). In another study, Van

Emmerik et al. demonstrated that individuals with PD show less adaptation in the relative phase between thoracic and pelvic rotations with changes in walking velocity (Van Emmerik et al., 1999). Movements of the thorax and pelvis were recorded for a group of individuals recently diagnosed with PD and a group of healthy age-matched controls. PD participants were in early stages of the disease (mean Hoehn and Yahr stage=1.5) and were not medicated. Participants walked on a treadmill. Speed of the treadmill was gradually increased and decreased within the same trial. Results showed that although in both groups relative phase between thoracic and pelvic rotations increased significantly as the walking velocity increased, PD participants consistently had significantly smaller relative phase than healthy controls (Van Emmerik et al., 1999). It should be noted that PD participants who participated in this study were in the early stages of the disease. Due to the progressive nature of Parkinson's disease and the poor response of axial symptoms to dopaminergic treatments (Agid, 1991) it is expected that over time the reduced ability to uncouple the rotation of the thorax and pelvis further diminish, leading to an in-phase movement of thorax and pelvis in advanced stages of the disease.

Stack and colleagues (2006) examined postural performance of PD participants during 180° turns while performing the everyday activity of making a cup of tea. PD participants were at stages II, III, and IV of Hoehn and Yahr scale and were tested "on" medication. Based on their report on the frequency of their turning difficulty, PD participants were assigned to either the difficulty turning (DT) or no difficulty turning (NDT) group. Both groups were videotaped while making a cup of tea in their own kitchen. To enhance the "normality" of the situation, the researcher engaged the participants in everyday conversation. PD participants

were also videotaped while making a standard "on-the-spot" turn. Two researchers blind to the participants' reports on turning difficulty evaluated the video-recordings. Results of this study showed that a large proportion (45%) of PD participants could not perform the task of making tea even in their "on" state. A greater proportion of PD participants in DT group than in NDT group appeared unstable while turning during the functional task. The DT group took more steps (up to 8 steps) while turning, lacked proper heel strike more frequently, and used external support more often. Furthermore, the report of difficulty turning was a sensitive predictor of the two key symptoms of PD locomotion: freezing and falling.

Although the DT group took more steps than the NDT group during the standard "on-the-spot" turns, 56% of participants across both groups took fewer steps when performing a functional turn than the standard on-the-spot turn. The discrepancy in step count between the two types of turns was greater in the DT group than in NDT group (Stack et al., 2006). Considering that the functional turns arose as the participants were pursuing another objective (making the tea) and they were also engaged in a conversation with the researcher, the fewer number of steps during functional turns is rather surprising. This finding emphasizes that standard tests commonly used in clinical settings may poorly reflect the individual's turning ability in real-life situations.

Willems and colleagues (2007) examined the turning performance of two groups of PD participants (freezers and non-freezers) and a group of healthy controls as they made a 180° left U turn. Participants were tested "on" medication and in two conditions: cued and non-cued. In the cued condition an auditory cue was presented with a rhythm equal to the

participant's comfortable step frequency during straight walking. Participants were instructed to synchronize their foot contacts with the beat of the cue. Results of this study showed that while making a 180° U turn, regardless of the cue condition PD participants took longer to turn and made wider turns with smaller and narrower steps than healthy age-matched controls. Authors suggested that PD participants may have adopted the "wide-arc" turning strategy to compensate for their inability to turn in the same way as the healthy individuals do. Adopting a wider arc during a turn could reduce the complexity of the task and make it easier to perform since it allows more gradual directional change (Willems et al., 2007). Freezers and non-freezers were not significantly different in the time to complete the turn, the number of steps taken to complete the turn, and step width in either cue conditions. The "wide-arc" turning strategy however, was more prominent in freezers than non-freezers in the non-cued condition. While cueing did not change the already wider turn of the freezers, it drove the non-freezers towards wider turns. Therefore, with auditory cue the difference in turn width of the two groups of PD participants disappeared (Willems et al., 2007).

In non-cued condition the variability of the step duration during turning was significantly higher for PD participants than healthy controls. Cueing reduced the variability of the step duration for both groups of PD participants; eliminating the difference in the step duration variability of healthy control and PD participants.

Crenna and colleagues examined the performance of fifteen healthy elderly and seven individuals with idiopathic PD as they made a 90º step turn to their left in the middle of their walk. PD participants were in the early stages of the disease (Hoehn &Yahr stage ≤ II),

demonstrated normal spatio-temporal gait parameters during straight walking, and had negligible or no axial rigidity. PD participants who were under medical treatment were tested while "on" medication (Crenna et al., 2007).

The time corresponding to the left heel strike of the step prior to the turning step (approaching step) was considered as the reference time and the time of initiation of reorientation of head and upper trunk was computed relative to the aforementioned reference time. Results showed that in healthy elderly head reorientation towards the new direction of travel initiated 80ms after the heel strike of the approaching step and preceded the reorientation of the upper trunk by 220ms. In PD participants however, there was a significant delay in initiation of reorientation of head resulting in simultaneous reorientation of head and upper trunk 340ms after the heel strike of the approaching step (Crenna et al., 2007).

Crenna and colleagues also divided each turn into two steps: the step that initiated the turn (from the right heel strike prior to the turn to the following left heel strike, called the "1st turn step"), and the step that completed the turn (from the left heel strike to the right heel strike after the turn, called the "2nd turn step"). The magnitude of head and upper trunk rotation was computed for the 1st and 2nd turn steps. Results showed that for healthy elderly during the 1st turn step the magnitude of head rotation was significantly greater than that of the upper trunk (52° vs. 38°, respectively). For PD participants however, the magnitudes of head and upper trunk rotation were not different from each other (25° for both segments) and were significantly smaller than the comparable values in healthy elderly. During the 2nd turn step,

PD participants showed greater rotation of head and trunk than during the 1st step. The magnitude of head and trunk rotation during the 2nd step was not different between the two groups (Crenna et al., 2007).

Crenna and colleagues argued that since the individuals with PD examined in their study were in the early stages of the disease, had no postural instability and/or axial rigidity and showed normal spatio-temporal gait parameters and lower limb kinematics during linear walking, basic locomotor deficits and/or axial rigidity cannot explain the impaired coordination of reorientation of their body segments. Authors suggested that task-specific pathophysiological mechanisms must underlie the impaired turning performance of PD participants. In comparison with linear walking, turning is a more challenging task that may require higher level of neural control, and may be more susceptible to functional impairment associated with PD (Crenna et al., 2007).

In a similar study, Carpinella and colleagues (2007) examined the turning performance of seven participants in the early stages (I and II Hoehn and Yahr scale) of PD and seven healthy age-matched controls. PD participants who were under medical treatment were tested while "on" medication. Participants were tested in straight walking and walking and turning conditions. In the latter condition participants made a 90º step turn to their left in the middle of their walk.

During straight walking, PD participants walked slower than the control group due to a mild decrease in cadence. However, other gait parameters that are usually affected in advanced stages of the disease (e.g. step length, duration of the single and double support phases of

gait) were not significantly different between the two groups. Furthermore, kinematic and kinetic analyses revealed no differences in range of motion, moment, and power of the lower limb joints.

Results of the turning trials revealed that PD participants turned slower and took more steps to complete the turn. Furthermore, the coordination of head and trunk reorientation was altered in PD participants. In healthy controls the reorientation of body segments towards the new direction of travel path followed a top-down strategy. Healthy elderly turned their head, upper trunk and pelvis 140, 280, and 370ms (respectively) after the heel strike of the approaching step. PD participants however, delayed the initiation of head reorientation and turned their head and upper trunk in an "en bloc" strategy. PD participants turned their head and shoulders simultaneously approximately 360ms after the heel strike of the approaching step, followed by rotation of pelvis about 140ms later (Carpinella et al., 2007).

The magnitude of head, upper trunk, and pelvis rotation during the step that initiated the turn (1^{st} turn step) and the step that completed the turn (2^{nd} turn step) was computed. During the 1^{st} turn step the magnitude of rotation of all three segments was significantly greater for healthy elderly than PD participants. The magnitude of head, upper trunk, and pelvis rotation at the end of the 1^{st} turn step was 46°, 39°, and 31° (respectively) for healthy elderly, and 25°, 25°, and 14° (respectively) for PD participants. During the 2^{nd} turn step, PD participants showed greater rotation of head and trunk; therefore, the magnitude of rotation of different body segments at the end of the 2^{nd} turn step was similar for the two groups. Authors concluded that individuals with PD in early stages of disease show mild changes of gait

parameters while walking on a linear path and more significant impairments during the transitional locomotor tasks such as turning (Carpinella et al., 2007).

Visser et al. (2007) examined turning performance of 24 PD participants while "on" medication and 25 healthy controls as they made 180° turns in the middle of their walk. Turning performance was examined in four different conditions: normal turn (self-paced turning), fast turn (turn as fast as possible), cued turn (turn suddenly upon an auditory cue), and dual tasking (turning while engaged in a secondary cognitive task). The peak angular velocity of the trunk in the yaw and roll planes was measured using angular velocity transducers (SwayStar system, Switzerland). Duration of the turn was also recorded (Visser et al., 2007).

Results revealed similar decrements in turning performance of PD participants relative to healthy elderly across all four turning conditions. Regardless of the turning condition, PD participants turned slower than healthy controls. Furthermore, for all turning conditions the trunk's peak yaw and roll angular velocities were lower for PD participants than for healthy controls. For both groups, dual tasking increased the duration of the turn, and decreased the peak yaw and roll angular velocities significantly. Results also showed a greater benefit in cueing for individuals with PD than controls. While the rapid turning task elicited the best performance in healthy elderly, performance of the PD participants further improved in the cued condition (Visser et al., 2007).

Visser et al. also showed that the trunk peak yaw and roll angular velocities obtained during turning could be used to discriminate individuals with PD and healthy controls. More

importantly, the trunk peak yaw and roll angular velocities obtained during turning have significantly higher discriminative values than the same measures obtained during straight walking (Visser et al., 2007).

Huxham and colleagues (2008) examined the turning behavior of 10 PD participants and 10 healthy controls as they made 60° and 120° step turns in the middle of their walk. PD participants were at stages II to III of Hoehn and Yahr scale, and demonstrated the typical slow and short-stepped walking pattern during straight walking. PD participants were tested "on" medication. Magnitude of head, thorax, and pelvis turn was measured at the three footfalls leading to and three footfalls exiting the turning point and also at constant distances relative to the turning point. To assess the intersegmental coordination the differences between the magnitudes of head and thorax, and thorax and pelvis turns at the six footfalls were also measured.

Results showed that, unlike what was expected, PD participants started to turn at an earlier footfall than the healthy controls and showed greater thoracic and pelvic rotation than the healthy control group at each distance from the turning point. Despite the ability to turn adequately, the coordination of body segments was impaired in individuals with PD. During both 60° and 120° turns thorax and pelvis were more tightly linked together in PD participants than in healthy controls as revealed by the reduced reciprocal oscillations between these segments in PD participants. This finding supports the clinical observation of the "en bloc" rotation of body in individuals with PD (Huxham et al., 2008).

Mak and colleagues (2008) examined turning performance of individuals with PD and healthy controls as they made sudden 30° and 60° turns during walking. PD participants were in stages II and III of Hoehn and Yahr scale and reported experiencing freezing of gait during daily activities. PD participants were tested "on" medication. Results showed that regardless of the magnitude of the turn, PD participants turned slower with narrower steps and demonstrated a longer delay in initiation of the mediolateral foot displacement. Group differences for the delayed onset of mediolateral foot displacement and step width were not affected by the magnitude of the turn. PD participants also showed a significant difference in the achieved and required magnitude of the turn during both 30° and 60° turns; with the achieved magnitudes always being smaller than the required ones. Nevertheless, there was no difference between the two groups in the onset times of head and trunk yaw relative to the turning cue delivery in either 30° or 60° turns. Magnitude of the turn did not affect the onset times of reorientation of body segments for either group (Mak et al., 2008). Although the relative timing of head and trunk turn were not statistically compared between the two groups, by careful examination of the graphs they do not appear to be different. Authors concluded that the main problem of individuals with PD during sudden turns lies in their inability to rapidly change the motor programs required for straight walking to turning, and this problem is independent of the magnitude of the turn (Mak et al., 2008).

Earhart et al. (2007) examined perception of active and passive turns of fifteen PD participants who demonstrated "en bloc" turning and eleven healthy age-matched controls in eyes-open and eyes-closed conditions. PD participants were tested "on" medication. The turns were 90°, 180°, 270°, and 360° to the right or left. For active turns, the direction and

the amplitude of the turn were specified and the participant was asked to turn in place in the specified direction and for the specified amount. For passive turns, participants stood on a rotating disc. They were told that the disc would rotate and were asked to press a button when they had turned for a specified amount. Results showed that although both groups tended to be more accurate during the active turns than the passive turns, PD participants were able to estimate the distance they had turned during both active and passive turns, even in the eyes-closed condition, as accurately as the healthy controls (Earhart et al., 2007). Similar to healthy controls, PD participants were able to accurately estimate the magnitude of the turn using any available sensory information, i.e., visual, vestibular, and proprioceptive information during active turns with eyes open; vestibular and proprioceptive information during active turns with eyes closed; visual and vestibular information during passive turns with eyes open; and only vestibular information during passive turns with eyes closed. Authors concluded that "turning difficulties in individuals with PD may more likely relate to motor or sensorimotor integration deficits than to pure sensory or sensory integration deficits" (Earhart et al., 2007).

1.5 Summary and purpose

While trips and slips are responsible for falls in young and elderly, many of the falls among the elderly are the result of altering the direction of travel (Tinetti et al., 1988; Cumming & Klineberg, 1994). Age-related modifications in turning execution increase the possibility of loss of balance and falls. Turning performance has been shown to predict the risk of falls in the elderly population, and therefore has been included in routine clinical assessments of functional balance in older adults. For example, 360° turns are incorporated into the "Berg

Balance Scale" and "Performance-Oriented Mobility Assessment" test batteries (Berg et al., 1989; Tinetti, 1986). Cumming and Klineberg (1994) showed that in healthy elderly, falling while turning was 7.9 times more likely to cause a hip fracture than falling while walking straight ahead. The greater incidence of hip fracture with falls that occur during turning while walking may be due to the fact that people who fall while turning are more likely to land on their side (and on their hip) than if the fall occurs while walking in a straight path. In individuals with PD, abnormal protective arm movements necessary to break the fall by an outstretched hand or by grabbing an external support (Carpenter et al., 2004) may further increase the incidence of a hip fracture in the event of a fall (Bloem et al., 2003). Stack and colleagues (2006) calculated the positive and negative predictive values, sensitivity, and specificity of the simple question "Do you have frequent difficulty turning?" in predicting the history of daily freezing and/or repeated falls in individuals with PD. They reported that difficulty in turning is a sensitive predictor of the two key symptoms of PD locomotion: freezing and falling (Stack et al., 2006). Therefore, it is imperative to identify the factors that contribute to the movement dysfunctions related to turning in the elderly population and in individuals with PD.

Impaired coordination of reorientation of axial body segments may contribute to turning-related dysfunctions. The purpose of this dissertation was to provide insight on the coordination of reorientation of axial body segments during turning in healthy elderly and individuals with PD. First the coordination of reorientation of different body segments during on-the-spot turns and turns embedded in locomotion is examined in a group of healthy

elderly. Incorporating two different degrees of turn in the protocol allowed examining the possible effect of the magnitude of the turn on the coordination of different body segments.

Ageing is accompanied with reduced gait velocity. Parkinson's disease further reduces the gait velocity of the individual. However, the effect of walking velocity on segment reorientation during walking turns has not been examined previously. The second study was designed to investigate the potential effect of walking velocity on segment reorientation during walking turns. Results of this study assist the interpretation of any differences that we might find in performance of our PD participants and healthy elderly, i.e., we will know to what extent the differences are accounted for by the differences in the gait velocity of the two groups and to what extent they are the direct result of the disease.

This thesis also examines how Parkinson's disease affects the turning performance of older adults during the on-the-spot turns (third study) and turns embedded in locomotion (fourth study). Unlike walking turns in which the body is in motion when the turn is initiated, standing turns require transition from static to dynamic state, reorientation of the body towards the new direction, and returning to the static state. Both transitions from static to dynamic state (Halliday et al., 1998; Martin et al., 2002; Rosin et al., 1997) and dynamic to static state (Oates et al., 2008) are impaired in individuals with Parkinson's disease. Therefore, we expected the performance of individuals with PD during the walking and standing turns be different from each other. For that reason, for individuals with PD standing and walking turns were examined in two separate studies. Possible effect of dopaminergic

medications on turning performance of individuals with PD is examined by testing the PD participants both “off” and “on” dopaminergic medications.

Chapter 2: Coordination of reorientation of different body segments during on-the-spot turns and turns embedded in locomotion in healthy older adults

2.1 Introduction

Almost every activity that involves locomotion requires turning. It is difficult to think of any activity, at home or community, which does not require some degree of on-the-spot turns or turns embedded in locomotion. On-the-spot turns and turns embedded in locomotion differ from each other and may require different motor control mechanisms. On-the-spot turns are initiated from a standing position and are completed by systematic reorientation of axial body segments towards the new direction. Turns embedded in locomotion however, require translation and rotation of the body towards the new direction of travel while continuing with the ongoing locomotion (Patla et al., 1991). Therefore, they necessitate changes in the anterior-posterior impulses, which are independent of the direction of the turn, to slow the locomotion speed along the sagittal plane; and changes in the mediolateral impulses, which are specific to the direction of the turn, to move the COM towards the new direction of travel (Patla et al., 1991). These modifications are accompanied by reorientation of different body segments towards the new direction of travel.

Clinical observations have identified turning as more challenging than straight walking for mobility-impaired individuals (Dite and Temple, 2002; Thigpen et al., 2000; Wall et al., 2000). Despite the prevalence of turning in daily activities and the challenge it poses to mobility-impaired individuals, there is far less research on turning than quiet standing and straight walking and the majority of these studies have examined performance of healthy young adults.

Studies examining performance of young healthy adults during turns embedded in locomotion have shown that they use a pivot strategy to turn with a ballistic, discrete motion with two or fewer steps (Thigpen et al., 2000) and prefer to proceed into the new direction by taking a step turn (Patla et al., 1991). Furthermore, while turning young healthy adults show a clear temporal sequence in initiation of rotation of different body segments; with movements in the yaw plane starting from the head and proceeding to the trunk and then to the feet in a top-down manner. This temporal sequence in initiation of rotation of different body segments in yaw plane is not related to a specific turning task; rather, it is evident during online steering (Paquette et al., 2008; Patla et al., 1999), discrete on-the-spot turns (Hollands et al., 2004), continuous on-the-spot turns (Earhart & Hong, 2006), and podokinetic after-rotations (Earhart & Hong, 2006).

Fewer studies have examined turning performance of the elderly population and have shown age-related modifications in turning execution for turns embedded in locomotion (Cao et al., 1997) and on-the-spot turns (Meinhart-Shibata et al., 2005) even in healthy and physically active older adults. In comparison with healthy young adults, healthy elderly are more variable in turn execution, turn slower, and take more steps to complete the turn during on-the-spot turns (Meinhart-Shibata et al., 2005) and turns embedded in locomotion (Thigpen et al., 2000; Cao et al., 1997). Research has revealed that in healthy older adults the temporal sequence of reorientation of body segments during turns embedded in locomotion is the same as healthy young adults, with the rotation of the head preceding the rotation of trunk (Paquette et al., 2008; Crenna et al., 2007; Carpinella et al., 2007; Fuller et al., 2007; Ferrarin

et al., 2006). To the best of our knowledge the sequence and timing of body segment reorientation during on-the-spot turns in elderly population have not been investigated yet.

The objective of the present study is to quantify and compare the sequence and timing of body segment reorientation in healthy elderly during on-the-spot turns and turns embedded in locomotion. Possible effect of magnitude of the turn on the coordination of reorientation of different body segments is also examined.

2.2 Methods

2.2.1 Participants

Nineteen healthy, physically active older adults, 10 males and 9 females, between the age of 60 to 75 years (mean±std age = 66±4.2 years) volunteered to participate in this study. The mean and standard deviation of the participants' height and body mass were 170±11cm and 77±17kg, respectively. Volunteers were free from any neurological, musculoskeletal or vestibular impairment. Participants had no history of falls in the six months prior to the experiment as verified by self-report. All participants were informed about the experimental procedure before signing a consent form. All procedures were approved by the Office of Research Ethics, University of Waterloo.

2.2.2 Procedure

Participants were asked to change into tight-fitting clothing. Fourteen infra-red emitting diodes (IREDs) were mounted on fourteen anatomical landmarks of the participants' body to track the movements of their body. Twelve IREDs were mounted on the following anatomical landmarks bilaterally: ear, shoulder joint, anterior superior iliac spine, hip joint,

lateral malleolus, and the big toe. One IRED was mounted on the chin and another IRED was placed on the participants' chest approximately 5cm below the jugular notch.

Participants were tested in two blocks of trials. One block consisted of trials in which participants walked at their natural, self-selected speed a short distance of approximately 7m and in the middle of their walk turned to change their direction of travel (walking turns). The other block consisted of trials in which participants turned to reorient their whole body towards a new direction while standing (on-the-spot turns).

Experimental set up is shown in Figure 2.1. A circle (diameter = 50cm) was drawn on the lab floor to indicate the "turning zone." During the walking trials participants were asked to walk straight ahead for about 4m to reach the "turning zone" and then turn off at an angle of 45° or 90° to either their right or left and continue to walk for an additional 3m. Four pylons were placed at the end of the potential travel paths (at right-45°, right-90°, left-45°, left-90° relative to the turning zone) to provide a continuous visual cue about the direction of the turn.

Before each trial participants were advised about the direction and the magnitude of the turn for that trial, i.e., they were told towards which pylon they should walk. Participants were instructed to walk (with their arms crossed in front of their chest) straight forward until they reach the turning zone at which they were asked to turn into the designated path (without stopping at the turning zone) and to keep walking until they reached the pylon positioned at the end of that path. Participants were instructed not to adjust their step length to step on the turning zone. They were told that the circle was there to just guide them as to where about they should make their turn. Participants were able to comply with these instructions. None

of them stopped at the turning zone and no one attempted to step in the zone by adjusting his/her step length.

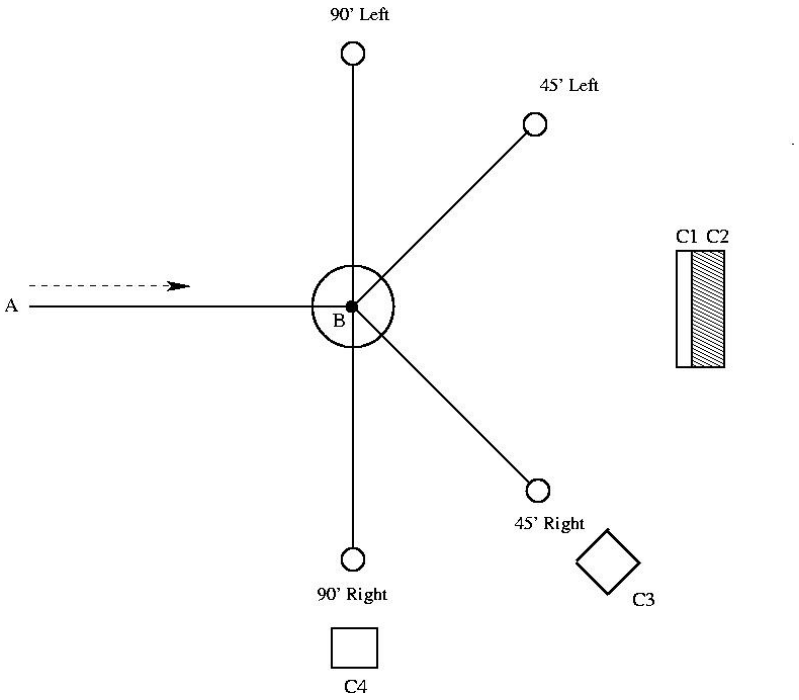


Figure 2.1. Figure shows the top view of the experimental set up. Walking trials started with participants standing at point A. On the straight walking trials participants walked straight ahead for about 7m and stopped in front of the two horizontal cameras (C1 and C2). During the walking and turning trials participants walked straight forward until they reached the turning zone (the large circle) at which they turned into the designated path and kept walking until they reached the pylon positioned at the end of that path. During the on-the-spot turns participants stood on the middle of the turning zone (B) and on the "go" signal turned to face one of the pylons positioned to their right or left at 45° or 90º. Small circles represent the pylons. C1 and C2 represent the two horizontal Optotrak cameras which were positioned on top of one another. C3 and C4 represent the two vertical cameras.

For the standing trials, participants stood on the middle of the turning zone with their arms crossed in front of their chest. Four pylons were placed at about 3m away from them at 45°

and 90° to their right and left. Before each trial the direction and magnitude of the turn was specified, i.e., participants were told towards which pylon they should turn. In each trial participants were instructed that on the "go" signal turn (with their whole body) to face the designated pylon.

Each participant performed three trials in each of the aforementioned conditions. Participants also performed three straight walking trials in which they were asked to walk straight ahead at their natural walking speed on a 7m path with their arms crossed in front of their chest. Therefore, each participant performed a total of 27 trials. However, data were collected only during the straight walking and right-turn trials (total of 15 trials). Participants were unaware that data were not being collected during the left-turn trials.

To minimize the possible effect of fatigue on the participants' performance the order of the blocks of walking and standing turns was counterbalanced across participants. Therefore, half of the participants performed the walking trials first and then proceeded to the standing trials while the other half performed the standing trials first and then proceeded to the walking trials. The straight walking trials were always performed at the beginning of the block consisting of the walking trials. The order of the right-turn and left-turn trials within each block was completely randomized.

Rest periods were provided throughout the experiment upon the participants' request. During the walking trials an assistant followed the participant closely to assist in the event of a fall. Throughout the experimental trials, movements of the participants' body were videotaped.

2.2.3 Data collection

Two horizontal and two vertical Optotrak 3D imaging system cameras (Northern Digital Inc., Canada) were used to collect kinematic data. The horizontal cameras were positioned on top of one another and were placed in front of the participant and at the end of the straight walking path. If only one camera was used, during the straight walking trials as the participant passed the turning zone and approached the camera the toe markers would fall outside of the camera's view. Therefore, two cameras were used at the end of the straight walking path. The bottom horizontal camera was tilted downward to allow capturing of the toe markers during the last part of the straight walking trials. This set up allowed collecting sufficient data during the straight walking trials. The vertical cameras were positioned at the participant's right side. This arrangement allowed collection of the data from two steps prior to two steps after the turning step. Optotrak data were recorded at 120 Hz.

2.2.4 Data processing

The Optotrak data were low-pass filtered (Butterworth) prior to analyses with a cut-off frequency of 6 Hz. The yaw angular displacement profiles of the head, shoulder (upper trunk), and pelvis in the global reference frame were determined from the three non-co-linear markers placed on each of the aforementioned segments. The three markers define the rigid body of each segment, making it possible to determine its orientation with respect to gravito-inertial frame.

For the standing trials, data collection started at least one second before the participant was instructed to turn. The initiation of reorientation of head, shoulder, and pelvis during the on-the-spot turns was calculated as the point in time that the angular displacement data indicated

the start of the turn towards the new direction, providing the deviation continued beyond the range of angular displacement of the segment during quiet stance.

For each participant, the mean and standard deviation values of the head, shoulder, and pelvis yaw during the three straight walking trials were calculated. For the walking turns the onset of change in the head, shoulder, and pelvis yaw orientation was calculated as the point in time that the angular displacement data indicated the segment had turned towards the new direction of the travel path, providing the deviation continued beyond the mean range of angular displacement of the segment during straight walking trials.

Toe displacement profiles were used to determine the onset of change in the mediolateral foot displacement towards the new direction. During the on-the-spot turns the onset of foot mediolateral deviation was calculated as the point in time that the test data deviated towards the designated direction providing the deviation continued beyond the range of displacement during quiet stance.

To determine the onset of change in mediolateral foot displacement during the walking turns, for each participant the data obtained from the three straight walking trials were averaged. Standard deviation (std) profiles over time were generated. The onset of foot mediolateral deviation into the designated travel direction during a walking and turning trial was calculated as the point in time that test data deviated from the control average profile providing the deviation continued beyond the control 2std boundary.

For both walking and standing trials, the onset of head reorientation towards the new direction was considered as the reference time (time = 0 ms). DT-Shoulder, DT-Pelvis and

DT-First Step refer to the delay time (DT) for reorientation of shoulder, pelvis, and the foot that took the first step towards the new direction (respectively) in the yaw plane relative to the aforementioned reference time.

For each trial the peak angular velocity of head, shoulder and pelvis in the yaw direction after the onset of the segment's movement was calculated. The time at which head reached its peak angular velocity in the yaw direction was considered the reference time (time = 0 ms). The latencies of the peak angular velocity of shoulder and pelvis relative to the aforementioned reference time were also computed.

2.2.5 Data Analyses

To explore the sequence and timing of the reorientation of body segments during turning and to examine the effect of condition (standing vs. walking) and magnitude of the turn (45° vs. 90°) on the aforementioned sequence and timing a four way repeated measure ANOVA with gender as between factor and body segment, condition, and magnitude of the turn as within factors was performed on the delay times (DTs) in the initiation of reorientation of body segments relative to the initiation of reorientation of the head. However, since the results of the aforementioned analysis revealed no significant main or interaction effect of gender on the variable of interest, the gender factor was removed. A three way repeated measure ANOVA with body segment (shoulder, pelvis, foot), condition (standing vs. walking), and magnitude of the turn (45°, 90°) as factors was performed to examine their possible effect on the latencies of the initiation of reorientation of body segments (DTs). Since the initiation of reorientation of head is considered as the reference time (time=0), head could not be included as a segment in the above analysis. Therefore, one-way t-tests were performed to determine if

the means of the delay times in the initiation of reorientation of shoulder, pelvis and foot are significantly different from zero (initiation of head reorientation). A Bonferroni correction was used to correct for multiple comparisons.

To compare the peak angular velocity of different body segments during the standing and walking turns and to examine the effect of gender and magnitude of the turn on the peak angular velocities a four way repeated measure ANOVA with gender as between factor and body segment (head, shoulder, pelvis), condition (standing vs. walking), and magnitude of the turn (45°, 90°) as within factors was performed on the peak angular velocities of the head, shoulder and pelvis. Results of the aforementioned analysis revealed no significant main or interaction effect of gender on the variable of interest. Therefore, the gender factor was removed; and a three way repeated measure ANOVA with body segment, condition, and magnitude of the turn as factors was performed to examine their possible effect on the peak angular velocities of the head, shoulder and pelvis.

To explore the sequence and timing of the peak angular velocity of different body segments during the standing and walking turns and to examine the effect of gender and magnitude of the turn on the aforementioned sequence and timing a four way repeated measure ANOVA with gender as between factor and body segment (shoulder, pelvis), condition (standing vs. walking), and magnitude of the turn (45°, 90°) as within factors was performed on the latencies of the peak angular velocity of shoulder and pelvis relative to the peak angular velocity of the head. Results revealed no main or interaction effect of gender on the variable of interest. Therefore, the gender factor was removed; and a three way repeated measure

ANOVA with body segment, condition, and magnitude of the turn as factors was performed to examine their possible effect on the latencies of the peak angular velocities of shoulder and pelvis.

In conditions that a main or interaction effect of a factor was revealed, Tukey's Studentized Range (HSD) Test was performed to determine which means were significantly different from the others. For all tests, a significance value (P) of less than 0.05 was used to test statistical significance.

2.3 Results

2.3.1 Sequence and Timing

In general, results show that during the on-the-spot turns healthy older adults turn their head, shoulder and pelvis in unison. The simultaneous reorientation of the head and trunk in the yaw plane is followed by reorientation of the feet (Figure 2.2). During the turns embedded in locomotion however, the temporal sequence in initiation of reorientation of different body segments in the yaw plane towards the new direction of the travel path follows a top-down manner starting from the head and proceeding to the shoulder, pelvis, and feet (Figure 2.3).

Results of the three way repeated measure ANOVA showed significant main effects of segment ($F(2,36)=215.94$, $P<0.0001$) and condition ($F(1,18)=48.07$, $P<0.0001$) on the delay times in the initiation of reorientation of different body segments relative to the initiation of reorientation of the head. Segment*condition ($F(2,36)=16.58$, $P<0.0001$), segment*magnitude ($F(2,36)=4.01$, $P=0.0268$), and segment*condition*magnitude ($F(2,36)=9.96$, $P=0.0004$) interaction effects were also significant. Tukey's analyses revealed

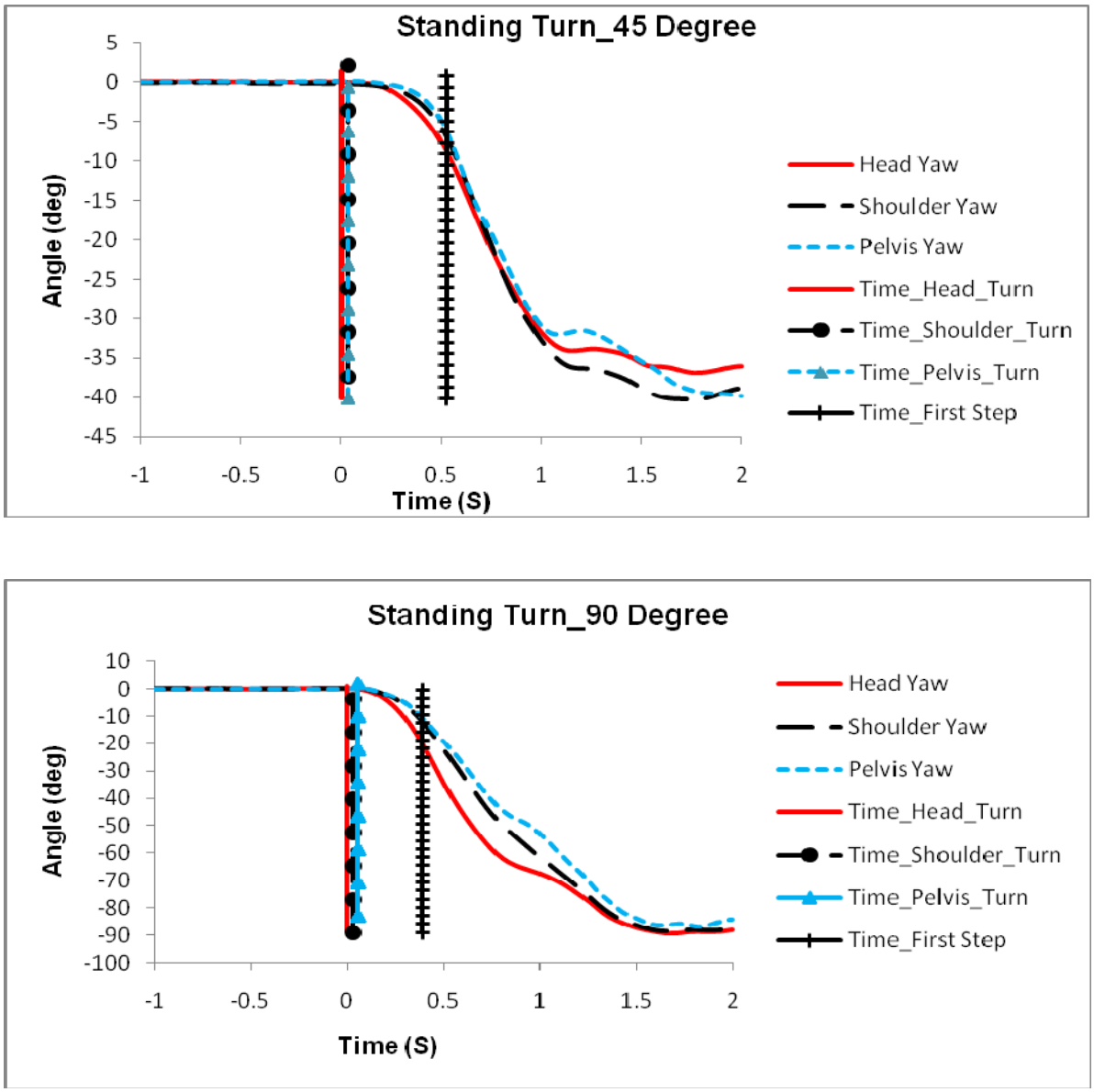
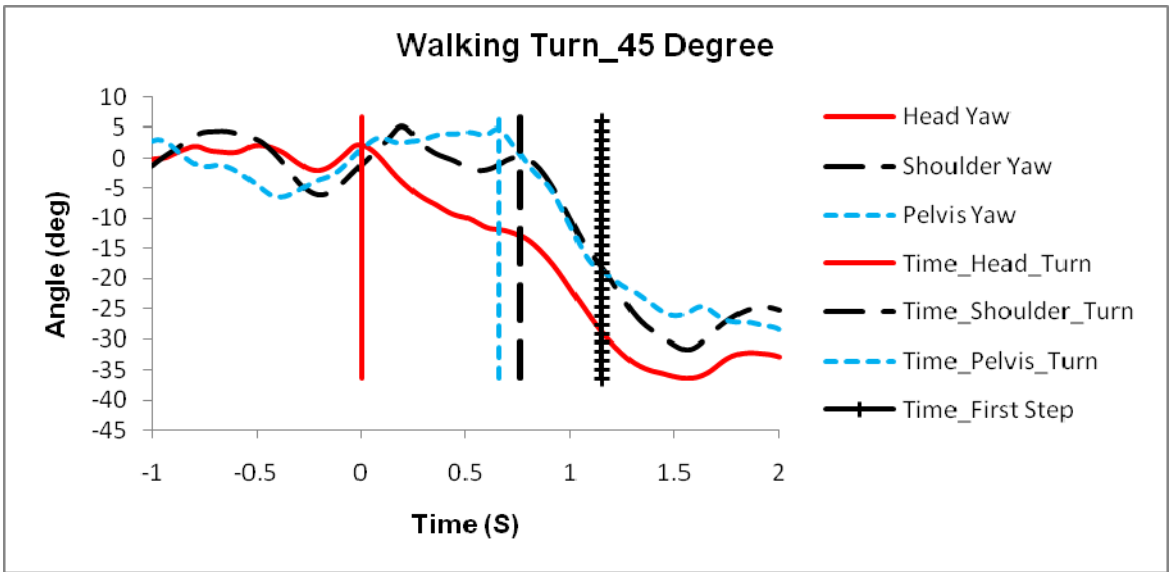


Figure 2.2. Figure shows the profiles of segmental reorientation of head, shoulder, and pelvis in the yaw plane during a 45° on-the-spot turn (top) and a 90° on-the-spot turn (bottom) for a representative participant. Zero is the time at which head reorientation towards the new direction initiated. Data has been plotted from 1s before to 2s after the initiation of reorientation of the head. Vertical lines indicate the time of initiation of reorientation of head, shoulder, and pelvis. The vertical lines with small crossing horizontal lines indicate the time of initiation of mediolateral displacement of the leading foot. Note that in the top figure the vertical lines indicating the initiation of reorientation of shoulder and pelvis are overlapped.



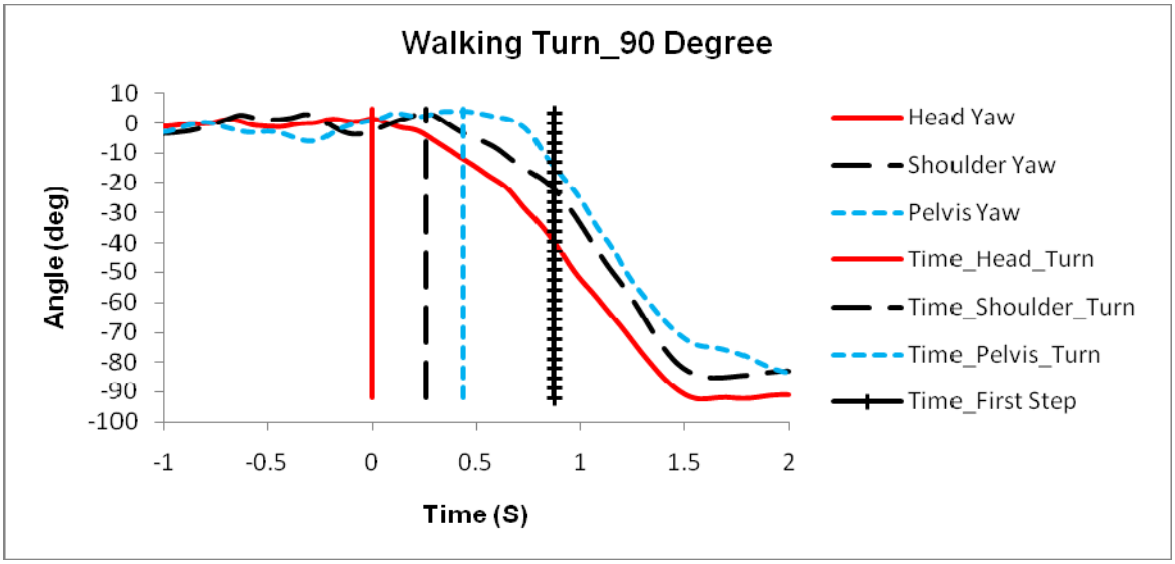


Figure 2.3. Figure shows the profiles of segmental reorientation of head, shoulder, and pelvis in the yaw plane during a 45° walking turn (top) and a 90° walking turn (bottom) for a representative participant. Zero is the time at which head reorientation towards the new direction initiated. Data has been plotted from 1s before to 2s after the initiation of reorientation of the head. Vertical lines indicate the time of initiation of reorientation of head, shoulder, and pelvis. The vertical lines with small crossing horizontal lines indicate the time of initiation of mediolateral displacement of the leading foot.

that during the on-the-spot turns regardless of the magnitude of the turn, DT-shoulder and DT-pelvis were not different from each other. However, DT-shoulder and DT-pelvis were significantly shorter than the DT-first step (mean±std = 18±54, -10±84, 360±113ms for DT-shoulder, DT-pelvis, and DT-first step, respectively) (Figure 2.4).

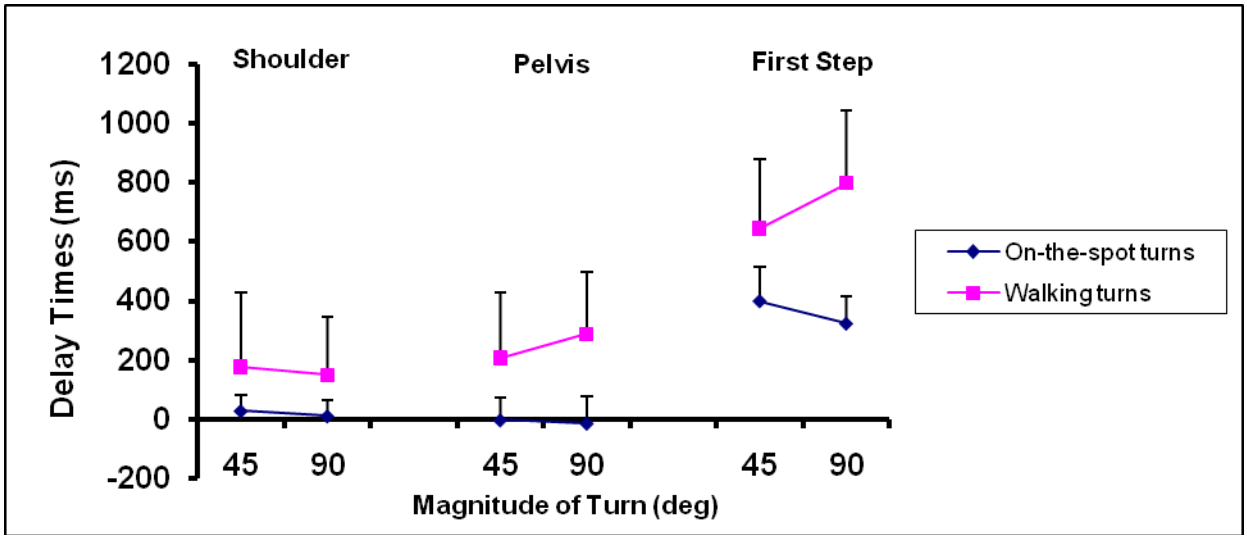


Figure 2.4. Mean and standard deviation (error bars) of the delay times (DTs) in the initiation of reorientation of shoulder, pelvis and foot in yaw plane relative to the initiation of head reorientation (DT-Shoulder, DT-Pelvis and DT-First Step, respectively) during the on-the-spot turns and walking turns at two different magnitudes of turn.

Furthermore, results of the one-way t-tests revealed that regardless of the magnitude of the turn DT-shoulder and DT-pelvis were not significantly different from zero. DT-first step however, was significantly different from zero during both 45° ($t=14.53$, $P<0.0001$) and 90° ($t=14.84$, $P<0.0001$) turns. These results indicate that during the on-the-spot turns, regardless of the magnitude of the turn, participants turned their head, shoulder, and pelvis

simultaneously. The simultaneous reorientation of the head and trunk in the yaw plane was followed by the mediolateral foot displacement.

Results of the walking trials revealed a considerable delay in the initiation of reorientation of shoulders and pelvis relative to the initiation of reorientation of the head during the 45° turns (mean±std=176±252 and 208±219ms for DT-shoulder and DT-pelvis, respectively) with no significant difference between DT-shoulder and DT-pelvis. During the 45° turns embedded in locomotion, DT-first step was significantly longer than DT-shoulder and DT-pelvis. The one-way t-tests revealed that DT-shoulder, DT-pelvis, and DT-first step were significantly different from zero ($t=3.08$, $P=0.0065$ for DT-shoulder; $t=4.15$, $P=0.0006$ for DT-pelvis; $t=12.05$, $P<0.0001$ for DT-first step). These results indicate that there was a significant delay in the initiation of reorientation of shoulder, pelvis, and first step relative to the reorientation of the head. The aforementioned results indicate that during the 45° turns embedded in locomotion, the reorientation of the body segments towards the new direction of the travel path starts with the reorientation of the head, followed by simultaneous reorientation of the shoulders and pelvis. Mediolateral foot displacement is the last (Figure 2.4).

During the 90° turns embedded in locomotion however, there was a significant delay in reorientation of all body segments. Mean and standard deviation of DT-shoulder, DT-pelvis, and DT-first step during the 90° walking turns were 150±198, 287±212, 798±249ms, respectively (Figure 2.4). The one-way t-tests revealed that these mean values were significantly different from zero ($t=3.30$, $P=0.0039$ for DT-shoulder; $t=5.91$, $P<0.0001$ for

DT-pelvis; t=14, P<0.0001 for DT-first step), indicating a significant delay in the initiation of reorientation of shoulder, pelvis, and first step relative to the initiation of head turn.

During the walking turns although there was no significant difference in DT-shoulder between the 45° and 90° turns (mean±std=178±252 and 150±198ms, respectively), DT-pelvis and DT-first step were significantly shorter during the 45° turns than during the 90° turns (Figure 2.4). Mean and standard deviation of the delay times during the 45° and 90° turns were 209±219 and 287±212ms for pelvis, and 644±233 and 798±284 ms for the first step, respectively.

2.3.2 Velocity

Results of the three way repeated measure ANOVA showed significant main effects of segment ($F(2,36)=22.98$, $P<0.0001$), condition ($F(1,18)=4.78$, $P=0.0422$), and magnitude of the turn ($F(1,18)=306.85$, $P<0.0001$) on the peak angular velocities of the head, shoulder, and pelvis. Segment*condition ($F(2,36)=9.90$, $P=0.0004$), segment*magnitude ($F(2,36)=21.03$, $P<0.0001$), and condition*magnitude ($F(1,18)=42.38$, $P<0.0001$) interaction effects were also significant.

Further examination of the significant segment*condition effect revealed that during the on-the-spot turns the peak angular velocity of shoulder and pelvis were significantly smaller than the peak angular velocity of the head. Mean and standard deviation of the peak angular velocities during the on-the-spot turns were 97.5±35.77, 79.98±28.87, and 78.11±25.47deg/s for head, shoulder, and pelvis, respectively (Figure 2.5).

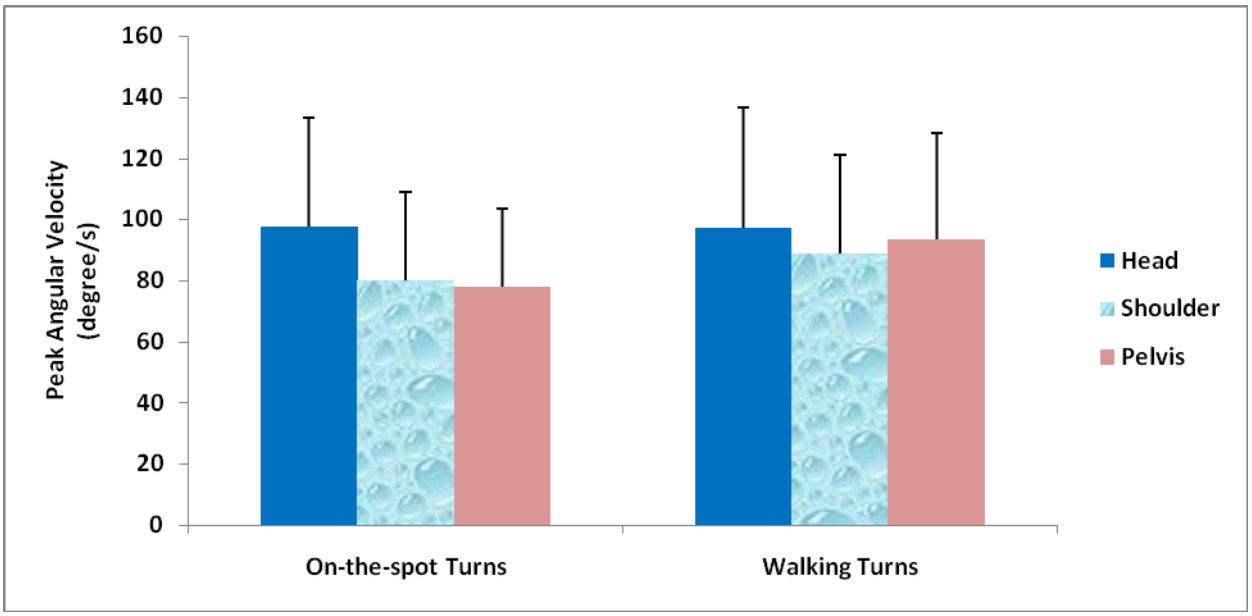


Figure 2.5. Mean and standard deviation (error bars) of the peak angular velocity of head, shoulder and pelvis during the on-the-spot turns and walking turns averaged across the two magnitudes of the turn.

Although the peak angular velocity of shoulder and pelvis were greater during the walking turns than the on-the-spot turns, the peak angular velocity of shoulder remained significantly smaller than the peak angular velocity of head. Mean and standard deviation of peak angular velocities during the walking turns were 97.08±39.32, 88.67±32.41, and 93.41±34.98deg/s for head, shoulder, and pelvis, respectively (Figure 2.5). Regardless of the condition, there was no significant difference between the peak angular velocity of shoulder and pelvis (Figure 2.5).

Examining the significant segment*magnitude interaction effect revealed that the peak angular velocity of all body segments were significantly greater during the 90° turns that

during the 45° turns (Figure 2.6). There was no significant difference among the peak angular velocity of different body segments during the 45° turns (mean±std=67.77±15.1, 63.26±16.58, and 64.31±15deg/s for head, shoulder, and pelvis, respectively). However, during the 90° turns the peak angular velocity of head was significantly greater than the peak angular velocity of shoulder and pelvis (mean±std=126.81±28.4, 105.38±27.15, and 107.21±28.68deg/s for head, shoulder, and pelvis, respectively) (Figure 2.6).

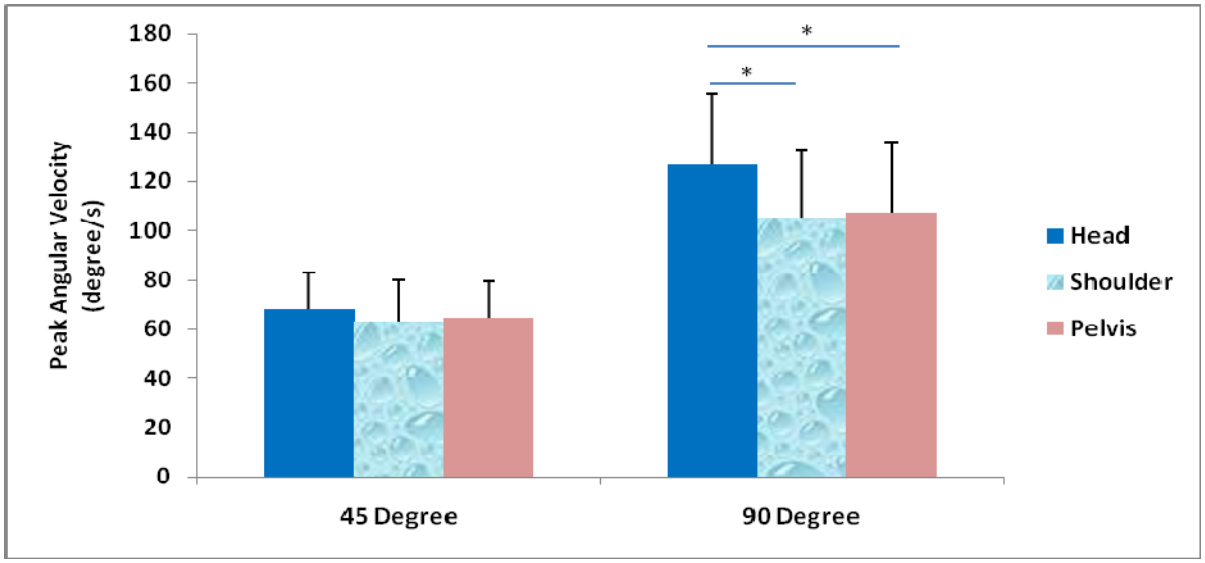


Figure 2.6. Mean and standard deviation (error bars) of the peak angular velocity of head, shoulder and pelvis during the 45º and 90º turns averaged across the two conditions.

The significant condition*magnitude effect revealed that averaged across all body segments there was no significant difference between the peak angular velocity during the on-the-spot turns and walking turns as the participants made 45º turns (mean±std= 67.25±18.22, and 62.98±12.13deg/s for the on-the-spot turns and walking turns, respectively) (Figure 2.7). However, during the 90º turns the peak angular velocity was significantly smaller for the on-

the-spot turns than the walking turns (mean±std=103.14±31.5, and 123.13±23.65deg/s for the on-the-spot turns and walking turns, respectively) (Figure 2.7).

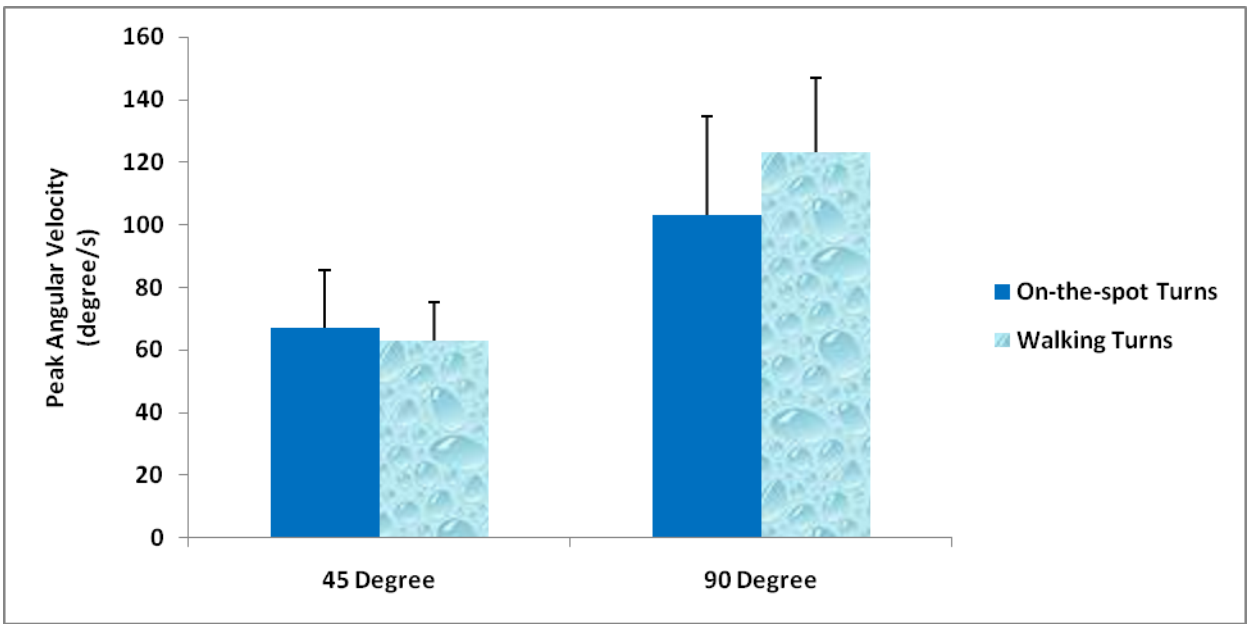


Figure 2.7. Mean and standard deviation (error bars) of the peak angular velocity, averaged across all body segments, at 45º and 90º turns during the on-the-spot turns and walking turns.

The three way ANOVA showed significant segment*magnitude interaction effect on the latencies of the peak angular velocity of the shoulder and pelvis relative to the peak angular velocity of the head ($F(1,18)=8.57$, $P=0.0090$). Tukey's analyses revealed that the latency of the peak angular velocity of pelvis was significantly smaller during the 45º turns than the 90º turns (mean±std=129.86±185.41 vs. 194.02±190.44ms). Furthermore, during the 45º turns the latency of the peak angular velocity of pelvis was significantly smaller than the latency of the peak angular velocity of shoulder (mean±std=129.86±185.41 vs. 179.68±216.58ms). During the 90º turns however, there was no significant difference between the latencies of the

peak angular velocity of shoulder and pelvis (mean±std=152.55±150.85 vs. 194.02±190.44ms, respectively) (Figure 2.8).

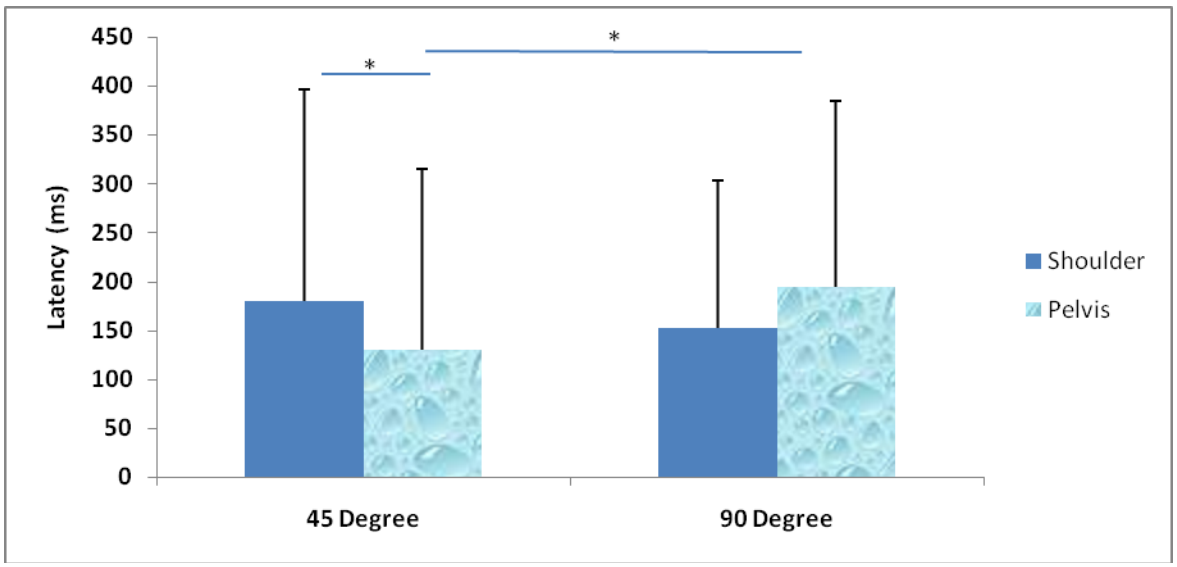


Figure 2.8. Mean and standard deviation (error bars) of the latencies of the peak angular velocity of shoulder and pelvis during the 45º and 90º turns averaged across the on-the-spot turns and walking turns. Stars indicate significant differences (α=0.05).

2.4 Discussion

This study examined the sequence and timing of body segment reorientation during on-the-spot turns and turns embedded in locomotion in healthy older adults. Effect of magnitude of the turn on the coordination of reorientation of different body segments was also examined.

During on-the-spot turns, regardless of the magnitude of the turn healthy older adults turned their head, shoulder, and pelvis in unison. The simultaneous reorientation of the head and trunk was followed by mediolateral foot displacement. During the walking turns however, the temporal sequence in initiation of reorientation of different body segments followed a

top-down manner and depended on the magnitude of the turn. While turning at 45°, healthy elderly turned their head first followed by simultaneous rotation of shoulder and pelvis, and lastly rotation of the feet. As the magnitude of the turn increased, there was a significant delay in initiation of rotation of all body segments.

Our results indicate that during on-the-spot turns the coordination of reorientation of different body segments in healthy elderly differ from what has been reported for healthy young adults. Research on healthy young adults has revealed a clear top-down temporal sequence in initiation of rotation of different body segments during discrete (Hollands et al., 2004) and continuous (Earhart and Hong, 2006) on-the-spot turns, with rotation starting from the head and proceeding to the trunk and the feet. Significant differences in the onset times of all body segments have been reported. Research has also revealed that in healthy young adults during the on-the-spot turns although the onset latencies are greater for larger turns, the top-down sequence and the significant differences among the onset times are preserved across different magnitudes of the turn (Hollands et al., 2004). The present study showed that during on-the-spot turns healthy elderly turn their head, shoulder, and pelvis in unison. This behavior was not affected by magnitude of the turn. Since the performance of our healthy elderly participants during the turns embedded in locomotion was similar to the performance of young adults, the simultaneous rotation of the head and body during the on-the-spot turns cannot be attributed to the age-related musculo-skeletal modifications. The simultaneous rotation of the head and body may be an adaptive strategy. During the on-the-spot turns, healthy elderly may reduce the degrees of freedom of movement by compiling different body segments to one; therefore, simplifying the control of movement. Grasso and colleagues

observed “en bloc” rotation of head and body as young children turned a 90° corner and attributed it to reducing the degrees of freedom to ease control of movement (Grasso et al., 1998). It is possible that during on-line steering, since different body segments are already in motion, our participants did not choose simultaneous segment rotation to avoid interfering with the ongoing locomotion.

Results of the trials including turns embedded in locomotion revealed a top-down temporal sequence in reorientation of body segments similar to what has been reported for healthy young adults (Grasso et al., 1998; Patla et al., 1999; Hollands et al., 2001) and healthy elderly (Ferrarin et al., 2006; Crenna et al., 2007; Carpinella et al., 2007); i.e., head turns first, then trunk, followed by the mediolateral foot displacement. Hollands and colleagues (2001) showed that during on-line steering if the head is immobilized on the trunk, young adults compensate for loss of independent head movement by turning their trunk significantly earlier. It should be noted that in the aforementioned study while the participant’s head was immobilized, the eyes were free to move within the head. Furthermore, the magnitudes of the turns were within a range that participants did not need to move their head in order to align gaze with the target. Therefore, the precedence of head turn over turning of other body segments cannot be attributed to its lower inertial constraints and/or to facilitation of alignment of gaze with the target. In fact anticipatory head turns have been reported for young adults as they walked along a 90° corner trajectory in both eyes-open and eyes-closed conditions (Grasso et al., 1998; Prévost et al., 2003). It is possible that the head turns first because the motor commands responsible for head turn are given earlier (Hollands et al., 2001). The anticipatory reorientation of the head in the new direction may provide the central

nervous system with allocentric and egocentric reference frames that can be used for effective subsequent reorientation of other body segments (Grasso et al., 1998; Hollands et al., 2001). The aforementioned hypothesis is supported by several neurophysiological studies that have reported existence of "head-direction cells" in the brain of rats (Blair and Sharp, 1995; Mizumori et al., 1993; Taube et al., 1995; Taube et al., 1990) and primates (Robertson et al., 1999). The "head-direction cells" are known to fire selectively when the animal's head is facing in a specific direction in space. The population of "head-direction cells" provides a continuous indication of the animal's directional heading (Blair and Sharp, 1995).

Although the literature is consistent in reporting the top-down sequence of body segments' rotation during the turns, the timing of body segment reorientation varies considerably across different studies. It should be noted that in the present study the timing of body segment reorientation was also highly variable as indicated by the large standard deviation values.

It is difficult to directly compare the timing of reorientation of body segments obtained in the present study with those from the previous studies since different studies have chosen different events as the reference for time zero. Furthermore, some studies have not examined the reorientation of the shoulder and pelvis separately; rather the trunk has been taken as one segment which makes the above comparison even more difficult. In the present study, averaged across the two magnitudes of the turn, during on-line steering the delay times in rotation of shoulder and pelvis were 164±224ms and 248±216ms, respectively. These values are smaller than what has been reported as the relative delay in trunk reorientation in healthy young adults by Patla et al. (1999) (300ms), and Grasso et al. (1998) (440 ms). Our results

are closer to the results of Carpinella et al. (2007) who showed delays of 140 and 230ms for upper trunk and pelvis relative to the head as healthy elderly made a 90° left turn in the middle of their walk, and the results of Paquette et al. (2008) who reported 228ms delay in rotation of trunk as healthy elderly made a 40° turn in the middle of their walk. Collectively, these studies suggest a tighter control of head and trunk in healthy elderly in comparison with healthy young adults during turns embedded in locomotion.

During both on-the-spot turns and turns embedded in locomotion, and for all body segments (head, shoulder, pelvis) the peak angular velocity was greater for 90° turns than 45° turns. In both conditions the peak angular velocity of head was greater and was reached earlier than the peak velocity of shoulder and pelvis. There was no difference in the peak angular velocity of the head between standing and walking turns. However, since the peak velocity of shoulder and pelvis was greater during turns embedded in locomotion, the difference in the angular velocity of head, shoulder and pelvis was less during turns embedded in locomotion than the on-the-spot turns.

Chapter 3: Coordination of turning when walking in healthy older adults: Effect of walking velocity

3.1 Introduction

Turning is essential for functional mobility and has a common occurrence in everyday life (Glaister et al., 2007). Turning while walking is a challenging component of locomotion. It requires translation and rotation of the body towards the new direction of travel while maintaining dynamic stability (Patla et al., 1991). Turning imposes changes in both anterior-posterior and mediolateral impulses in order to slow the locomotion speed along the sagittal plane and move the COM towards the new direction of travel (Patla et al., 1991). It necessitates asymmetric tuning of the step lengths and ground reaction forces to redirect the cyclical movement of the lower limbs (Orendurff et al., 2006; Courtine and Schieppati, 2003). Failure to make the necessary adjustments associated with turning results in increased difficulty in navigation, and consequently greater risk of fall.

Patla and colleagues (1999) divided turns embedded in locomotion into two different types: step turn (turning to the opposite side of the stance limb, e.g. going to the right with the right limb while the left foot is on the ground) and spin turn (turning towards the stance limb, e.g. going to the right with the left limb while the right foot is on the ground). Step turns allow greater stability and have less biomechanical cost than spin turns (Patla et al., 1991; Taylor et al., 2005). During the step turns, the COM always remains within the base of support. Furthermore, step turns require increasing the level of activity of the muscles which are already active, while spin turns require inhibiting one group of muscles and activating another group and increasing the magnitude of activity in these newly recruited muscles to an appropriate level (Patla et al., 1991; Taylor et al., 2005). Patla and colleagues (1991) showed

that when no specific instructions are given regarding the turn type, healthy young adults prefer to make a step turn.

Numerous studies (Grasso et al., 1996; Grasso et al., 1998; Patla et al., 1999; Hollands et al., 2001; Prévost et al., 2003) have examined the sequence of reorientation of different body segments during turns embedded in locomotion in healthy young adults. These studies either did not control for the turn type (Grasso et al., 1996; Grasso et al., 1998; Prévost et al., 2003) or instructed the participants to turn in a specific direction with a specified foot landing on the floor so that all trials were performed with the same type of turn (generally step turn) (Patla et al., 1999; Hollands et al., 2001). Findings of the aforementioned studies are consistent in that the rotation of body segments proceeds from the head to the trunk and the feet in a top-down manner. These studies have revealed that head turn precedes the rotation of the trunk regardless of direction and/or magnitude of the turn (Grasso et al., 1996; Grasso et al., 1998; Patla et al., 1999; Hollands et al., 2001), visual condition (Grasso et al., 1998; Prévost et al., 2003), and walking speed (Prévost et al., 2003). Therefore, the head first strategy is considered "a stable and reproducible, i.e., an invariant characteristic of human locomotion" (Prévost et al., 2003).

Fewer studies (Crenna et al., 2007; Carpinella et al., 2007; Fuller et al., 2007; Ferrarin et al., 2006) have examined the sequence and timing of reorientation of different body segments during turns embedded in locomotion in healthy elderly. These studies have only examined the step turns, and revealed a similar top-down sequence in reorientation of body segments.

A recent study by Paquette et al. (2008) is the only study that has examined the sequence and timing of reorientation of different body segments in healthy young and older adults during both step and spin turns. Performance of six healthy young and six healthy elderly was examined as they made 40° turns to their right or left. The starting foot and/or the walking start point were adjusted to require participants to perform two different types of turns: step and spin turns. Results revealed similar timing and sequence in segment reorientation in young and older adults as they approached the turn point. More importantly, turn type had no significant effect on the sequence and timing of segment reorientation for either group of participants (Paquette et al., 2008).

Both ageing and Parkinson's disease are accompanied by slowing of gait. For healthy elderly the slower gait is the result of reduction of both cadence and step length. For individuals with PD however, the slower gait is primarily due to the reduced step length since cadence remains within the normal range of the healthy age-matched controls (O'Sullivan et al., 1998). Research has shown that when healthy young adults walk either slower or faster than their comfortable walking speed, their movements become more variable (Dingwell and Marin, 2006; Oberg et al., 1993; Winter, 1983). Furthermore, dynamic stability of the upper body and lower limb joints decreases as the walking velocity increases (England and Granata, 2007; Dingwell and Marin, 2006).

Few studies provide insight on the effects of walking velocity on the coordination of head during turning. Prévost and colleagues (2003) examined the spatio-temporal patterns of head reorientation as healthy young adults turned along a 90° corner at three different speeds:

natural speed, 1.5 times slower, and 1.5 times faster. Results showed that, regardless of the walking velocity, the head deviated towards the inner part of the curved path. While walking velocity did not affect the magnitude of the head turn, it did affect the timing of head reorientation. The head started to turn at a constant distance (rather than at a constant time) to the corner; therefore, the head turn was initiated earliest for the slowest velocity (Prévost et al., 2003). Prévost and colleagues did not comment on the effect of walking velocity on the relative timing of reorientation of head, trunk and feet.

Grasso and colleagues (1996) showed that when young healthy adults were asked to walk at a constant speed along circular trajectories of different radius, their linear and angular velocities changed with the change of the curvature of the path. As the radius of the path decreased, i.e., the turn became sharper, participants' linear velocity decreased and their angular velocity increased. Grasso et al. also demonstrated that while head yaw systematically anticipated changes of the direction of locomotion by 100-200ms, the duration of anticipation depended on the curvature of the trajectory; it was longer for trajectories with shorter radius (sharper turns) (Grasso et al., 1996). The effect of gait velocity on coordination of segment reorientation during turning has not been investigated yet.

The purpose of the present study was: 1) to examine if healthy elderly participants show a preference to initiate their turn with a step turn or a spin turn as they turn in the middle of their walk, 2) to examine whether the turn type (step vs. spin) affects the timing and sequence of reorientation of different body segments, 3) to investigate the possible effect of walking velocity on timing and sequence of body segment reorientation, and whether this effect

depends on the magnitude of the turn. It is hypothesized that healthy elderly prefer the step turns due to the advantages they offer, i.e., greater stability and lower biomechanical cost. In light of the findings of Paquette et al. (2008), we anticipate the sequence of reorientation of body segments to remain the same across the two turn types. Changes in walking velocity may alter the onset times and the relative timing of reorientation of body segments; however, we expect the sequence of reorientation of different body segments remain the same across different walking velocities.

3.2 Methods

3.2.1 Participants

Nineteen healthy, physically active older adults, 10 males and 9 females, between the age of 60 to 75 years (mean±std age = 66±4.2 years) volunteered to participate in this study. The mean and standard deviation of the participants' height and body mass were 170±11cm and 77±17kg, respectively. Volunteers were free from any neurological, musculoskeletal or vestibular impairment. Participants had no history of falls in the six months prior to the experiment as verified by self-report. All participants were informed about the experimental procedure before signing a consent form. All procedures were approved by the Office of Research Ethics, University of Waterloo.

3.2.2 Procedure

Participants were asked to change into tight-fitting clothing. Fourteen infra-red emitting diodes (IREDs) were mounted on fourteen anatomical landmarks of the participants' body to track the movements of their body. Twelve IREDs were mounted on the following

anatomical landmarks bilaterally: ear, shoulder joint, anterior superior iliac spine, hip joint, lateral malleolus, and the big toe. One IRED was mounted on the chin and another IRED was placed on the participants' chest approximately 5cm below the jugular notch.

Participants were tested in three blocks of trials: 1) walking at their natural, self-selected speed, 2) walking at half their natural walking speed, and 3) walking at double their natural walking speed. All participants completed the trials at their natural walking speed first, and then proceeded with the trials at slower or faster than their natural walking speed. However, to minimize the possible effect of fatigue on the participants' performance the order of the blocks of trials with slower and faster velocities was counterbalanced across participants. Therefore, for half of the participants the order of blocks was "natural velocity, slow, fast" while for the other half the order was "natural velocity, fast, slow."

Each block of trials consisted of three straight walking trials and twelve trials of walking and turning. The experimental setup is shown in Figure 3.1. In the straight walking trials participants were asked to walk straight ahead on a 7m path with their arms crossed in front of their chest. During the walking and turning trials participants were asked to walk straight ahead for about 4 meters to reach the "turning zone" and then turn off at an angle of 45° or 90° to either their right or left and continue to walk for an additional 3 meters. A circle (diameter = 50cm) was drawn on the lab floor to indicate the "turning zone." A pylon was placed at the end of each of the potential travel paths to provide a continuous visual cue about the direction of the turn. Before each trial participants were advised about the direction and the magnitude of the turn for that trial, i.e., they were told towards which pylon they

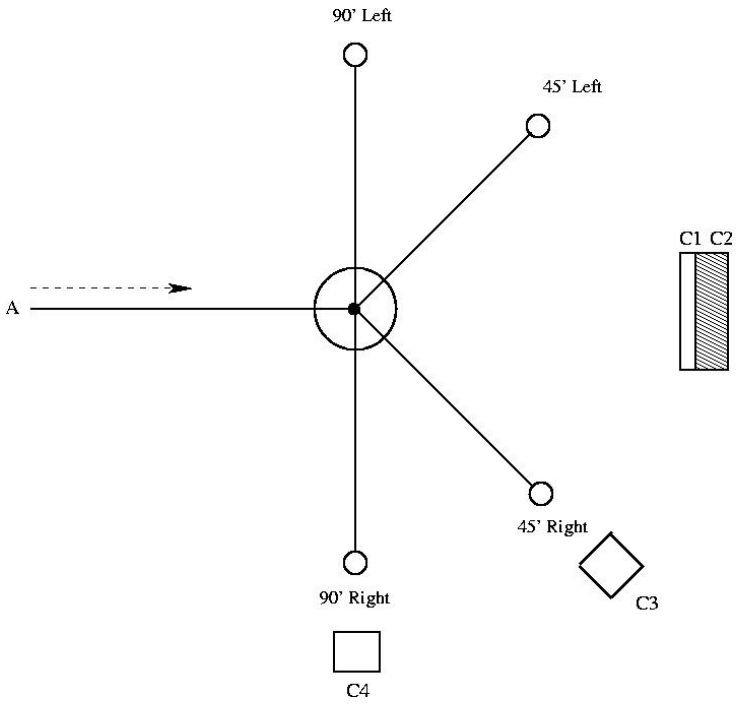


Figure 3.1. Figure shows the top view of the experimental set up. Trials started with participants standing at point A. On the straight walking trials participants walked straight ahead for about 7m and stopped in front of the two horizontal cameras (C1 and C2). During the turning trials participants walked straight forward until they reached the turning zone (the large circle) at which they turned into the designated path and kept walking until they reached the pylon positioned at the end of that path. Small circles represent the pylons. C1 and C2 represent the two horizontal Optotrak cameras which were positioned on top of one another. C3 and C4 represent the two vertical cameras.

should walk. Participants were instructed to walk straight forward until they reach the turning zone at which they were asked to turn into the designated path (without stopping at the turning zone) and to keep walking until they reach the pylon positioned at the end of that path. Participants were instructed not to adjust their step length to step on the turning zone. They were told that the circle was there to just guide them as to where about they should make their turn. All participants were able to comply with these instructions. None of them

stopped at the turning zone and no one attempted to step in the zone by adjusting his/her step length. The three straight walking trials were always performed at the beginning of each block. The order of the right-turn and left-turn trials within each block was completely randomized. Each participant performed three trials in each of the aforementioned conditions. Therefore, each participant performed a total of 45 trials. However, data were collected only during the straight ahead and right-turn trials (a total of 27 trials). Participants were unaware that data were not being collected during the left-turn trials.

Rest periods were provided throughout the experiment upon participants' request. During the trials an assistant followed the participant closely to assist in the event of a fall. Throughout the experimental trials, movements of the participants' body were videotaped.

3.2.3 Data collection

Two horizontal and two vertical Optotrak 3D imaging system cameras (Northern Digital Inc., Canada) were used to collect kinematic data. The horizontal cameras were positioned on top of one another and were placed in front of the participant and at the end of the straight walking path. If only one camera was used, during the straight walking trials as the participant passed the turning zone and approached the camera the toe markers would fall outside of the camera's view. Therefore, two cameras were used at the end of the straight walking path. The bottom horizontal camera was tilted downward to allow capturing of the toe markers during the last part of the straight walking trials. This set up allowed collecting sufficient data during the straight walking trials. The vertical cameras were positioned at the participant's right side. This arrangement allowed collection of the data from two steps prior to two steps after the turning step. Optotrak data were recorded at 120 Hz.

3.2.4 Data Processing

The Optotrak data were low-pass filtered (Butterworth) prior to analyses with a cut-off frequency of 6 Hz. For each trial, walking velocity was calculated using the data obtained from the two markers placed on the big toes. The distance traveled by the toe markers from the time that these markers came into the cameras' view to the time that they fell out of the cameras' view (equivalent to at least four steps for both straight walking and turning trials) was calculated. Walking velocity was computed by dividing the distance traveled by the time it took to travel that distance. Excluding the initial and final portions of the trial (i.e., before the toe markers came to the cameras' view and after they fell out of the cameras' view) eliminated the confounding effects of acceleration and deceleration on calculations of the walking velocity.

The yaw angular displacement profiles of the head, shoulder (upper trunk), and pelvis in the global reference frame were determined from the three non-co-linear markers placed on each of the aforementioned segments. The three markers define the rigid body of each segment, making it possible to determine its orientation with respect to gravito-inertial frame. For each participant and for each walking velocity, the mean and standard deviation values of the head, shoulder, and pelvis yaw during the three straight walking trials were calculated. The onset of change in each body segment's yaw orientation during a turning trial was calculated as the point in time that the angular displacement data indicated the segment had turned towards the new direction providing the deviation continued beyond the mean range of angular displacement of the segment during straight walking trials.

Toe displacement profiles were used to determine the onset of change in the mediolateral foot displacement towards the new direction of the travel path for the right and left feet. For each participant and in each walking velocity the data obtained from the three straight walking trials were averaged. Standard deviation (std) profiles over time were generated. For the turning trials, the onset of foot mediolateral deviation into the designated travel direction was calculated as the point in time that test data deviated from the control average profile providing the deviation continued beyond the control 2std boundary. The onset times of the reorientation of the feet towards the new direction of the travel path were examined to determine whether the first step was taken with the right or the left foot (step vs. spin turn).

The onset of head reorientation towards the new direction of travel path was considered as the reference time (time = 0 ms). DT-Shoulder, DT-Pelvis and DT-First Step refer to the delay time (DT) for reorientation of shoulder, pelvis, and the foot that took the first step, regardless the preparatory or main step (for definition of the preparatory step see below), towards the new direction of the travel path (respectively) in the yaw plane relative to the aforementioned reference time.

For each turning trial the peak angular velocity of head, shoulder and pelvis in the yaw direction after the onset of the segment's movement was calculated. The time at which the head reached its peak angular velocity in the yaw direction was considered the reference time (time = 0 ms). The latencies of the peak angular velocity of shoulder and pelvis relative to the aforementioned reference time were also computed.

Examining the data revealed that in many trials the reorientation of each foot towards the new travel direction was completed over two steps rather than one; a *preparatory step* with small deviation of the foot towards the new direction of the travel path and a *main step* with significant mediolateral deviation of the foot towards the new direction of the travel path. The prevalence of the preparatory steps was examined by calculating, for each foot, the magnitude of mediolateral displacement towards the new direction of the travel path for the first two steps following the onset of reorientation of the foot towards the new direction (step 1 and step 2). If the magnitude of mediolateral displacement towards the new direction of the travel path during step 1 was less than one third of the comparable value for the step 2, the step 1 was considered a preparatory step. The turns completed with a preparatory and a main step were labeled as the *double-step turns*.

3.2.5 Data Analyses

A one way repeated measures analysis of variance (ANOVA) with walking velocity as a factor was performed on the data obtained from the turning trials to examine whether the participants followed the instructions regarding their walking velocity, i.e., to walk with equal, half or double their natural walking speed.

For each walking condition the percentages of trials with double-step and single-step turns were calculated to provide an estimate of the prevalence of the preparatory steps in turning performance of the healthy elderly. A binomial proportion test was used to test the significance of the differences in prevalence of the double-step and single-step turns in different conditions.

To determine if healthy older adults had a preference for step turn vs. spin turn, the percentages of the step turns (in which the *main step* initiating the reorientation towards the new direction was taken with the right foot) and the spin turns (in which the *main step* initiating the reorientation towards the new direction was taken with the left foot) were computed. A binomial proportion test was used to test the significance of the differences in percentages of step and spin turns in different conditions.

To explore the sequence and timing of the reorientation of different body segments during the turning trials and to examine the effect of gender, walking velocity and the magnitude of the turn on the aforementioned sequence and timing, a four way repeated measure ANOVA with gender as the between factor and body segment, velocity, and magnitude of the turn as within factors was performed on the delay times (DTs) in the initiation of reorientation of different body segments relative to the initiation of reorientation of the head. However, since the results of this analysis revealed no main or interaction effect of gender on the variable of interest, the gender factor was removed. A three way repeated measure ANOVA with body segment (shoulder, pelvis, foot), velocity (slow, natural, fast) and the magnitude of the turn (45°, 90°) as factors was performed to examine their possible effect on the latencies of the initiation of reorientation of body segments (DTs). Since the initiation of reorientation of head is considered as the reference time (time=0), head could not be included as a segment in the above analysis. Therefore, one-way t-tests were performed to determine if the means of the delay times in the initiation of reorientation of shoulder, pelvis and foot are significantly different from zero (initiation of head reorientation). A Bonferroni correction was used to correct for multiple comparisons.

To compare the peak angular velocity of different body segments during the turning trials and to examine the effect of gender, walking velocity, and the magnitude of the turn on the peak angular velocities, a four way repeated measure ANOVA with gender as the between factor and body segment, velocity, and magnitude of the turn as within factors was performed on the peak angular velocities of the head, shoulder and pelvis. Results revealed no main or interaction effect of gender on the peak angular velocity values; therefore, the gender factor was removed. A three way repeated measure ANOVA with body segment (head, shoulder, pelvis), velocity (slow, natural, fast) and the magnitude of the turn (45°, 90°) as factors was performed to examine their possible effect on the peak angular velocity values.

To explore the sequence and timing of the peak angular velocity of different body segments and to examine the effect of gender, walking velocity, and the magnitude of the turn on the aforementioned sequence and timing, a four way repeated measure ANOVA with gender as the between factor and body segment (shoulder, pelvis), velocity (slow, natural, fast), and magnitude of the turn (45°, 90°) as within factors was performed on the latencies of the peak angular velocity of the shoulder and pelvis relative to the peak angular velocity of the head. Results revealed no main or interaction effect of gender on the timing of the peak angular velocity values; therefore, the gender factor was removed. A three way repeated measure ANOVA with body segment, velocity, and the magnitude of the turn as factors was performed to examine their possible effect on the sequence and timing of the peak angular velocity values.

In conditions that a main or interaction effect of a factor was revealed, Tukey's Studentized Range (HSD) Test was performed to determine which means were significantly different from the others. For all tests, a significance value (P) of less than 0.05 was used to test statistical significance.

3.3 Results

The velocity data indicated that the participants followed the instructions regarding their walking speed. Mean and standard deviation of the walking velocity for the slow, natural, and fast walking during the straight walking trials were 0.59±0.13, 1.02±0.15, and 1.41±0.18 m/s respectively (Figure 3.2). The mean and standard deviation of the walking velocity during the turning trials at different speeds were comparable to the mean and standard deviation of the walking velocity during the straight walking trials at the corresponding speeds (Figure 3.2).

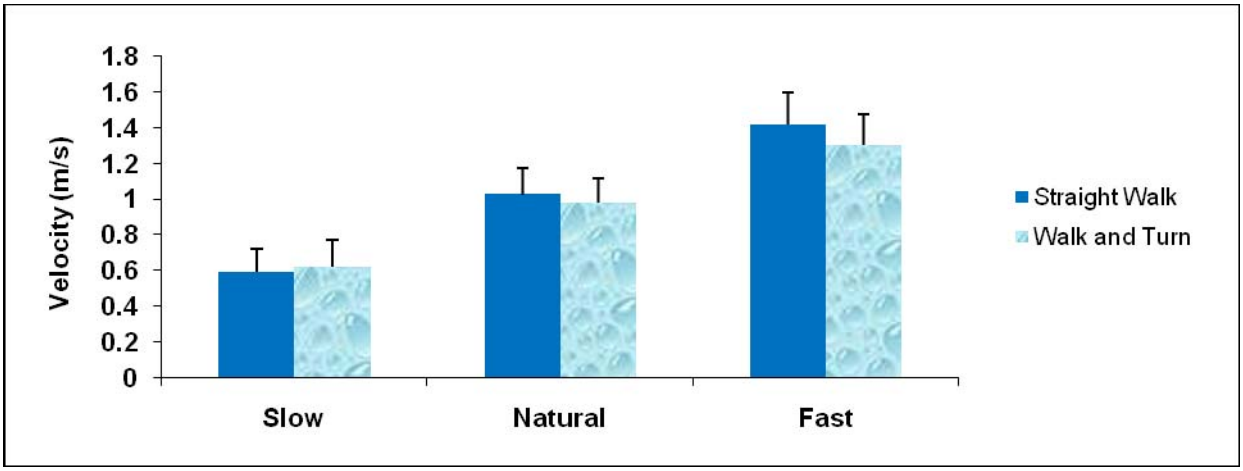


Figure 3.2. The mean and standard deviation (error bars) of the walking velocity during the straight walking and turning trials (averaged across the two magnitudes of the turn) at three different walking speeds (slow, natural, and fast).

Results of the one way ANOVA on the data obtained from the turning trials revealed a significant difference in the participants' walking velocity among the slow, natural speed, and fast turning trials ($F(2,36)=209.17$, $P<0.0001$). Averaged across the two magnitudes of the turn, the mean and standard deviation of the walking velocity for the slow, natural speed, and fast turning trials were 0.62±0.15, 0.98±0.14, and 1.30±0.18 m/s, respectively. This result indicates that although not at their half and double natural speed, participants did walk significantly slower (63.3%) than their natural speed during the slow turning trials and significantly faster (132.7%) than their natural speed during the fast turning trials (Figure 3.2).

Figure 3.3. shows the percentage of the double-step turns (turns including a *preparatory step* and a *main step)* and single-step turns at different turning conditions. Binomial proportion test revealed significant differences in prevalence of the double-step and single-step turns during the 45º turns while walking slow ($Z=-2.5456$, $P=0.0153$) and at natural speed ($Z=-2.8316$, $P=0.0065$), and 90º turns while walking fast ($Z=3.0464$, $P=0.0032$). Single-step turns were more common during 45º turns while walking at slow and natural speeds (68% and 69.1%, respectively), while double-step turns were more common during 90º turns while walking fast (70.2%).

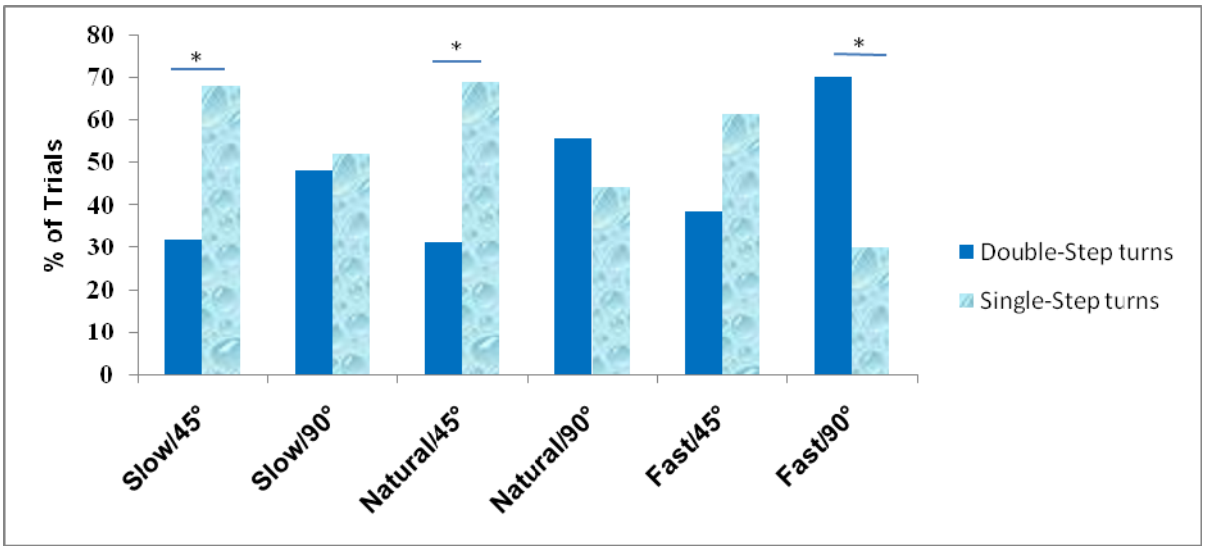


Figure 3.3. The percentage of trials with double-step and single-step turns at each of the six different combinations of the velocity and magnitude of the turn. Stars indicate significant differences (α=0.05).

3.3.1 Effect of turn type on the timing and sequence of reorientation of different body segments

Figure 3.4. shows the percentage of the step turn vs. the spin turn across different conditions. Binomial proportion test revealed no significant difference in the percentage of the step turn and spin turn at any condition. This result indicates that regardless of the velocity and magnitude of the turn, healthy elderly showed no preference in making a step turn or a spin turn.

The effect of turn type (step vs. spin) on the timing and sequence of reorientation of different body segments towards the new direction of travel was examined by comparing DT-Shoulder, DT-Pelvis, and DT-First Step obtained from the trials performed with the two different types of turn at each velocity*magnitude condition. Results showed no significant

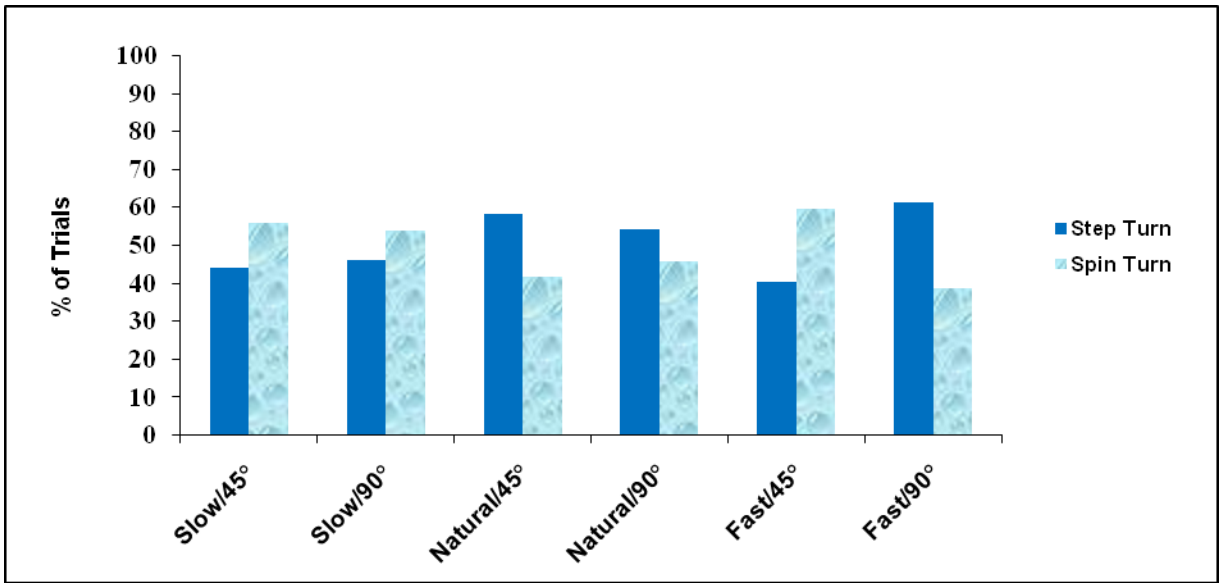


Figure 3.4. The percentages of the step turn vs. spin turn at the six different combinations of the velocity and magnitude of the turn.

difference between the step and spin turns in the timing and sequence of reorientation of different body segments towards the new direction of travel at any speed condition for both 45° and 90° turns. Therefore, data obtained from all trials (regardless of the turn type) were pooled together and used in the subsequent analyses.

3.3.2 Sequence and Timing

In general, results show that in healthy older adults regardless of the walking velocity the temporal sequence in initiation of reorientation of different body segments in the yaw plane towards the new direction of the travel path follows a top-down pattern starting from the head and proceeding to the shoulder, pelvis, and feet (Figure 3.5, Figure 3.6, Figure 3.7).

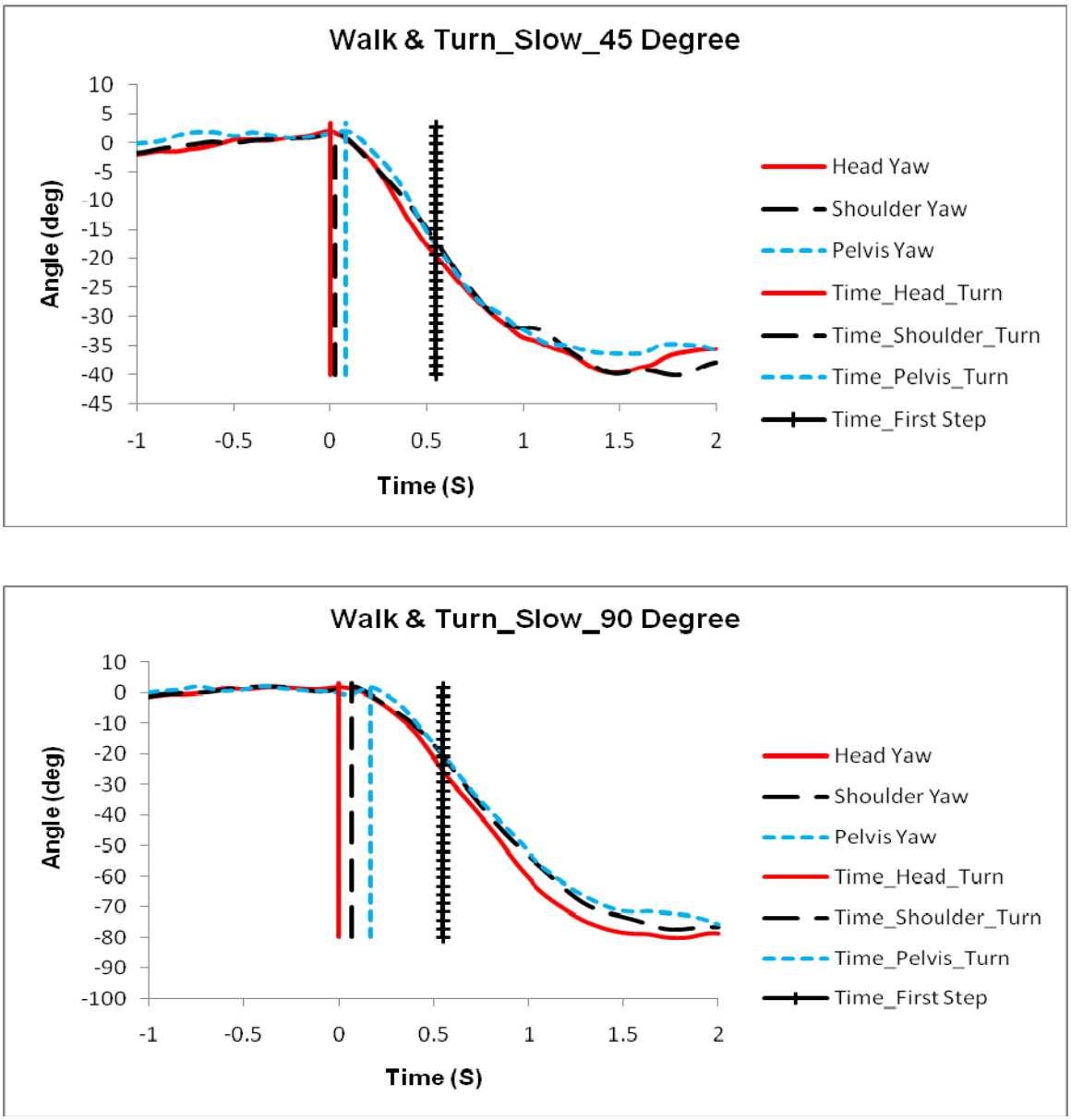
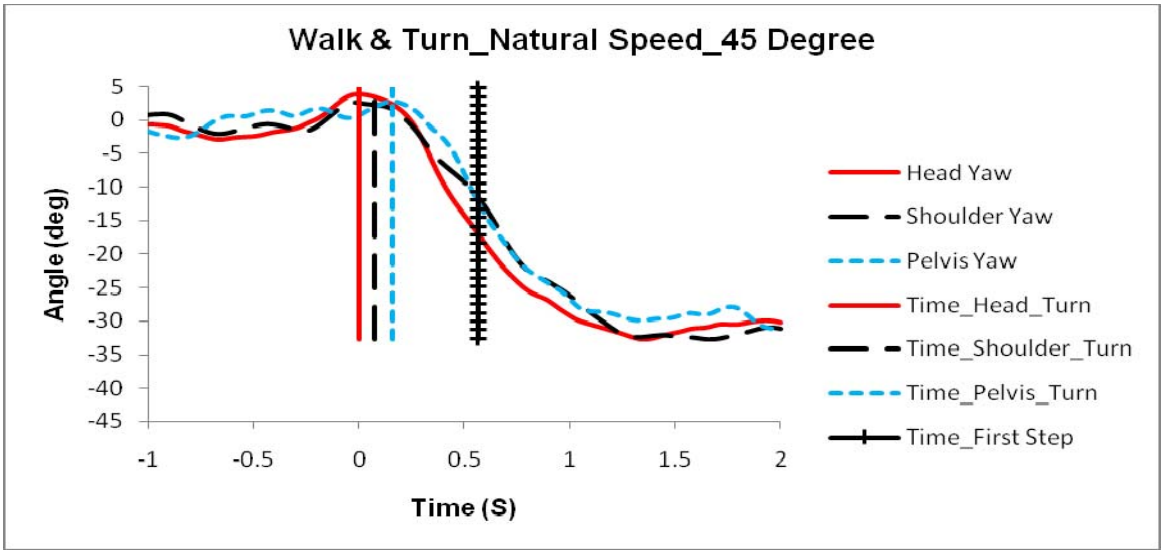


Figure 3.5. Profiles of segmental reorientation of head, shoulder, and pelvis in the yaw plane during a 45° (top) and a 90° (bottom) turn while walking at slow speed for a representative participant. Zero is the onset time of head turn. Data is plotted from 1s before to 2s after the initiation of head turn. Vertical lines indicate the time of initiation of reorientation of head, shoulder, and pelvis. The vertical lines with small crossing horizontal lines indicate the time of initiation of mediolateral displacement of the leading foot.



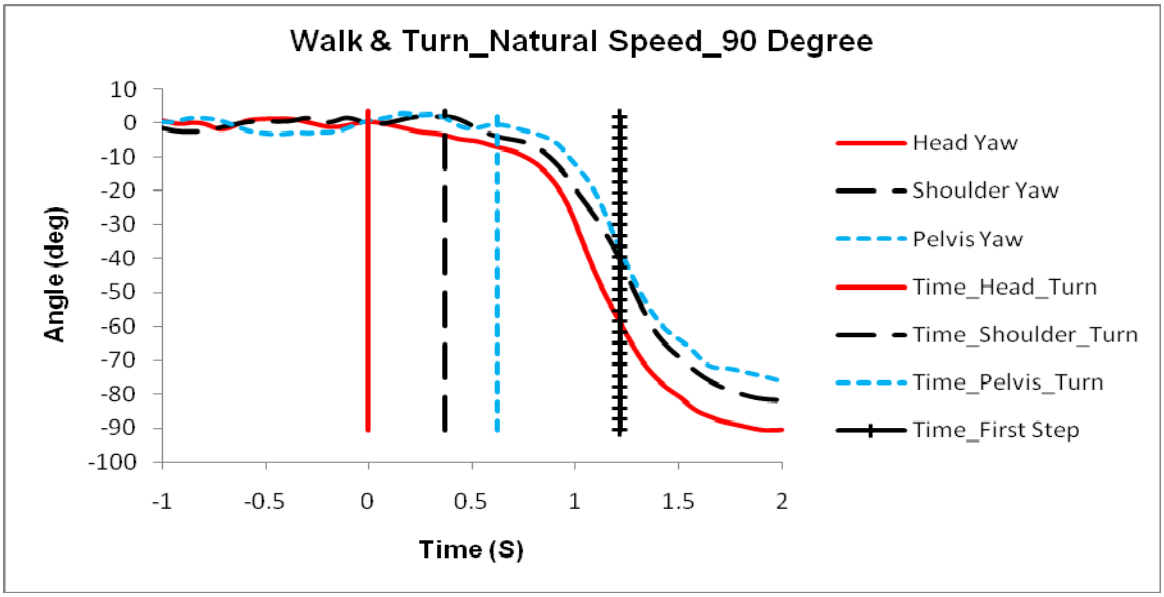
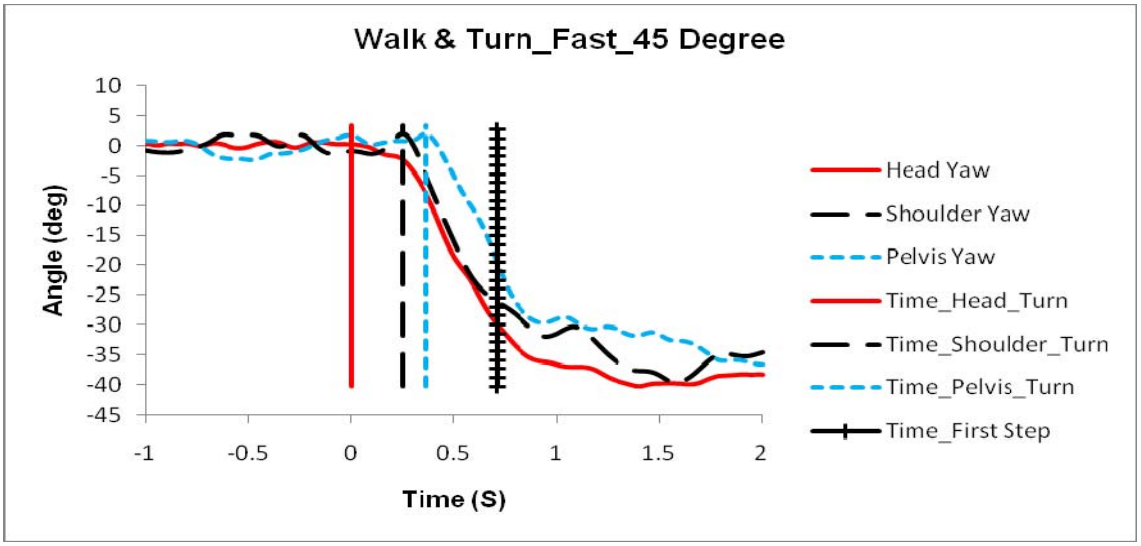


Figure 3.6. Profiles of segmental reorientation of head, shoulder, and pelvis in the yaw plane during a 45° (top) and a 90° (bottom) turn while walking at natural speed for a representative participant. Zero is the onset time of head turn. Data is plotted from 1s before to 2s after the initiation of head turn. Vertical lines indicate the time of initiation of reorientation of head, shoulder, and pelvis. The vertical lines with small crossing horizontal lines indicate the time of initiation of mediolateral displacement of the leading foot.



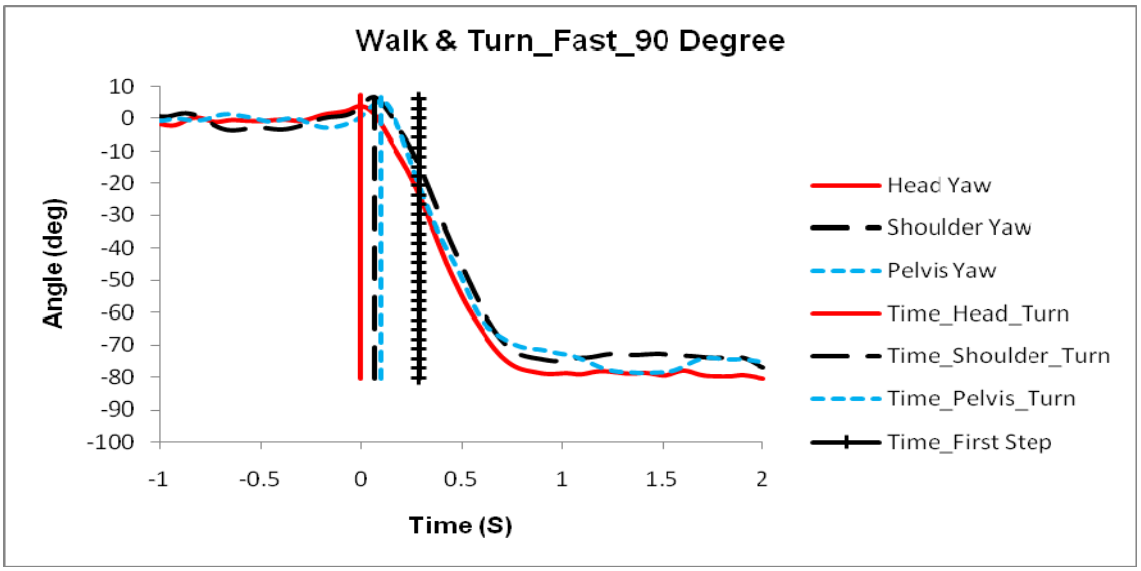


Figure 3.7. Profiles of segmental reorientation of head, shoulder, and pelvis in the yaw plane during a 45° (top) and a 90° (bottom) turn while walking at fast speed for a representative participant. Zero is the onset time of head turn. Data is plotted from 1s before to 2s after the initiation of head turn. Vertical lines indicate the time of initiation of reorientation of head, shoulder, and pelvis. The vertical lines with small crossing horizontal lines indicate the time of initiation of mediolateral displacement of the leading foot.

Results of the three way ANOVA revealed a significant effect of body segment. Regardless of the walking velocity and magnitude of the turn, DT-Shoulder, DT-Pelvis, and DT-First Step were significantly different from each other ($F(2,36)=136.53$, $P<0.0001$). Averaged across different walking speeds and magnitudes of the turn, reorientation of the shoulder, pelvis and foot towards the new direction initiated at 144, 251, and 710ms (respectively) after the initiation of reorientation of the head. Furthermore, results of the one-way t-tests revealed that the abovementioned values were significantly different from zero ($t=7.17$, $P<0.0001$ for DT-shoulder; $t=10.84$, $P<0.0001$ for DT-pelvis; $t=24.70$, $P<0.0001$ for DT-first step). These results indicate that regardless of the walking velocity and magnitude of the turn, reorientation of different body segments towards the new direction of travel path followed a top-down pattern starting from the head and proceeding to the shoulder, pelvis, and feet.

The three way ANOVA also revealed a significant segment*velocity interaction effect ($F(4,72)=6.80$, $P=0.0001$) on the delay times in the initiation of reorientation of different body segments. Tukey's analyses revealed that DT-First Step was significantly different among different turning velocities; being longest during the slow turns and shortest during the fast turns (Figure 3.8). The mean and standard deviation values of the DT-First Step during the slow, natural speed, and fast turns were 786±337, 721±250, and 623±313ms, respectively.

Unlike DT-First Step, DT-Pelvis was significantly longer during fast turning trials than during the slow turning trials (mean±std = 293±257 vs. 213±267ms). DT-Pelvis during the natural speed turns was not significantly different from the comparable values during the

slow and fast turning trials (Figure 3.8). There was no significant difference in DT-shoulder across different velocities of walking (mean±std = 103±210, 164±224, and 167±212ms for the slow, natural, and fast walking speeds, respectively) (Figure 3.8).

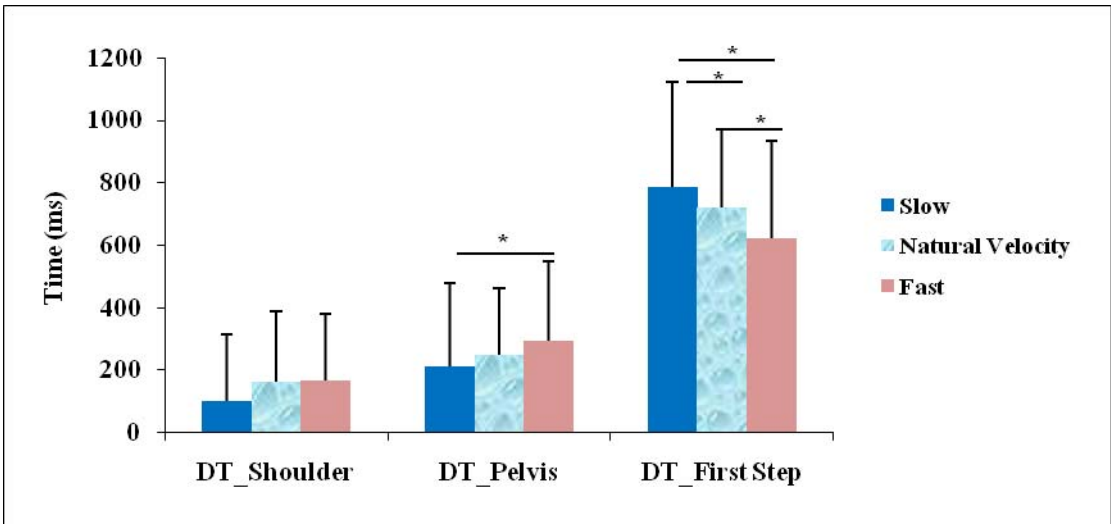


Figure 3.8. The mean and standard deviation (error bars) of the delay times in the initiation of reorientation of shoulder, pelvis and foot in the yaw plane relative to the initiation of reorientation of the head (DT-Shoulder, DT-Pelvis, and DT-First Step, respectively) during turning at slow, natural, and fast walking velocities averaged across the two magnitudes of turn. Stars indicate significant differences (α=0.05).

The segment*magnitude of the turn interaction effect on the delay times in the initiation of reorientation of different body segments relative to the initiation of reorientation of the head was also significant ($F(2,36)=11.28$, $P=0.0002$). Tukey's analyses revealed that DT-First step was significantly larger during the 90° turns than during the 45° turns (mean±std = 777±320 vs. 643±280ms). DT-shoulder and DT-pelvis remained unchanged across different magnitudes of turn (Figure 3.9).

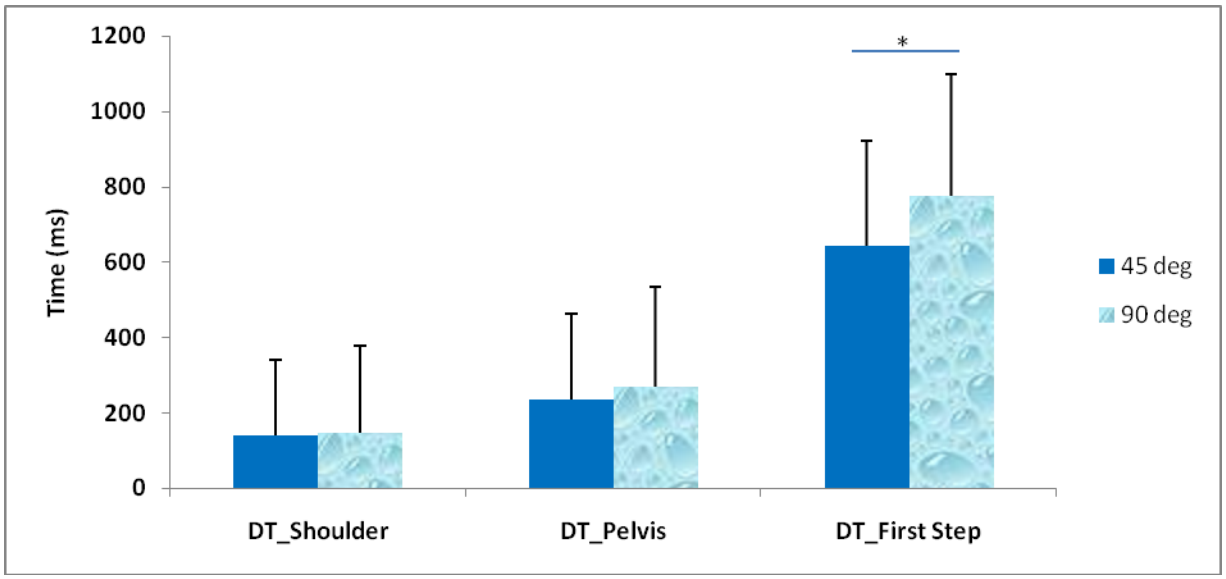


Figure 3.9. The mean and standard deviation (error bars) of the delay times in the initiation of reorientation of shoulder, pelvis, and foot in the yaw plane relative to the initiation of reorientation of the head (DT-Shoulder, DT-Pelvis, and DT-First Step, respectively) at two different magnitudes of the turn averaged across different velocities. Star indicates significant difference (α=0.05).

3.3.3 Velocity

The three way ANOVA on the peak angular velocity values showed significant effects of body segment ($F(2,36)=8.23$, $P=0.0011$), velocity ($F(2,36)=52.73$, $P<0.0001$), and magnitude of the turn ($F(1,18)=370.97$, $P<0.0001$). Velocity*magnitude ($F(2,36)=6.46$, $P=0.0040$), and segment*magnitude ($F(2,36)=10.30$, $P=0.0003$) interaction effects were also significant. The significant velocity*magnitude interaction effect revealed that averaged across all body segments the peak angular velocities at each level of magnitude of the turn were significantly different at different velocities of walking, being smallest for the slow turns and largest for the fast turns (Figure 3.10). The mean and standard deviation of peak angular velocity were

48.62±10.8, 62.98±12.1, and 75.71±17.8deg/s during the 45° turns, and 96.37±19.4, 123.13±23.7, and 136.12±29.9deg/s during the 90° turns at slow, natural, and fast walking speeds, respectively (Figure 3.10).

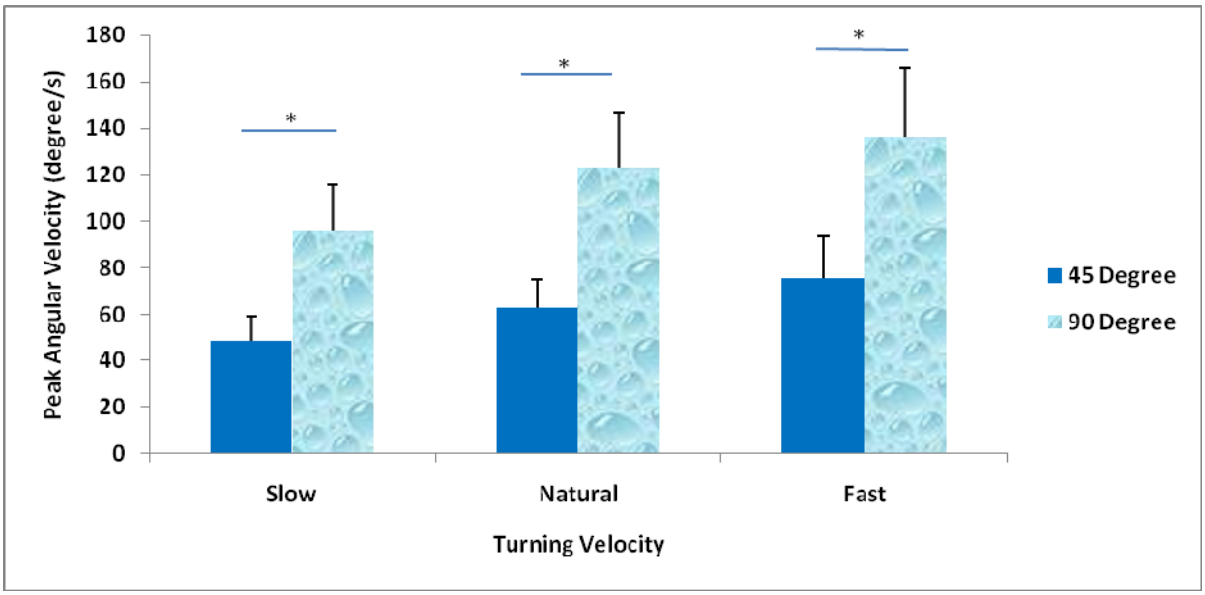


Figure 3.10. The mean and standard deviation (error bars) of the peak angular velocity during the slow, natural speed, and fast turns at two different magnitudes of turn averaged across all participants and all body segments (head, shoulder, and pelvis).

Examining the significant segment*magnitude interaction effect revealed that the peak angular velocity of different body segments was significantly greater during the 90° turns than during the 45° turns (Figure 3.11). During 45° turns the peak angular velocity of head, shoulder, and pelvis were not significantly different from each other (mean±std = 60.71±16.9, 61.86±17.8, and 64.74±18.5deg/s, respectively). During 90° turns however, the peak angular velocities of head and pelvis were significantly larger than the peak angular

velocity of shoulder (mean±std = 125.11±30.1, 110±24.7, and 120.5±32.1deg/s for head, shoulder, and pelvis, respectively) (Figure 3.11).

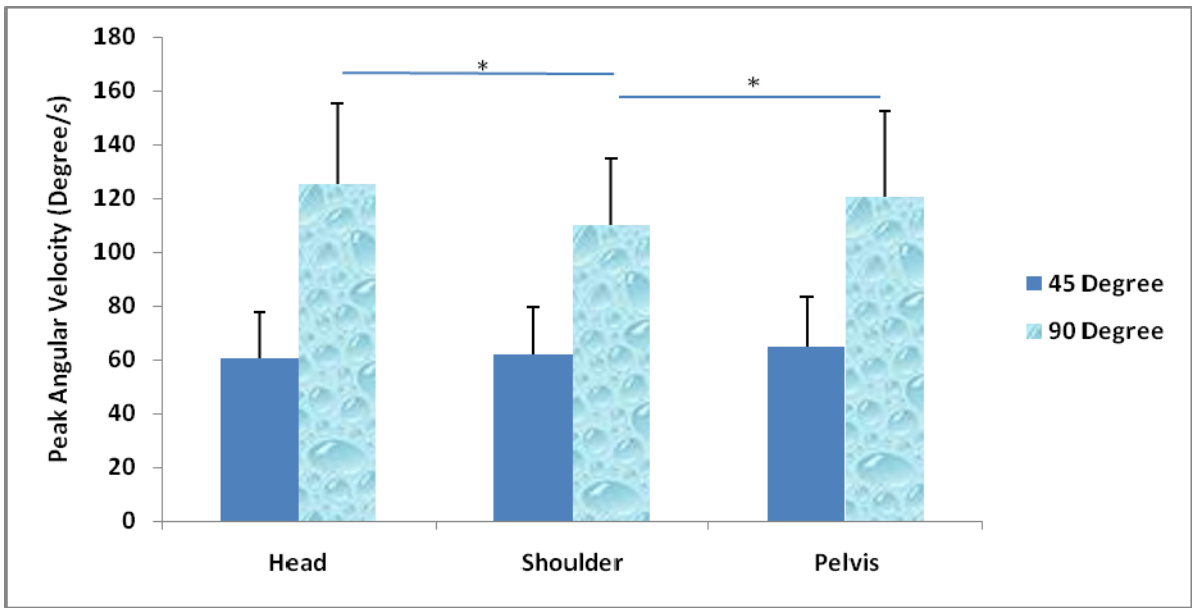


Figure 3.11. The mean and standard deviation (error bars) of the peak angular velocity of head, shoulder, and pelvis at two different magnitudes of turn averaged across all participants and all walking velocities. Stars indicate significant differences (α=0.05).

As mentioned in the *Data Analyses*, to explore the sequence and timing of the peak angular velocity of different body segments and to examine the effect of walking velocity, and magnitude of the turn on the aforementioned sequence and timing, a three way repeated measure ANOVA was performed on the latencies of the peak angular velocity of shoulder and pelvis relative to the peak angular velocity of the head. Results revealed a significant segment*velocity*magnitude interaction effect ($F(2,36)=4.27$, $P=0.0217$). Tukey's analyses revealed that regardless of the magnitude of the turn, the latency of the peak angular velocity

of shoulder increased as the walking velocity increased; however, this change was greater during 90º than 45º turns (Figure 3.12).

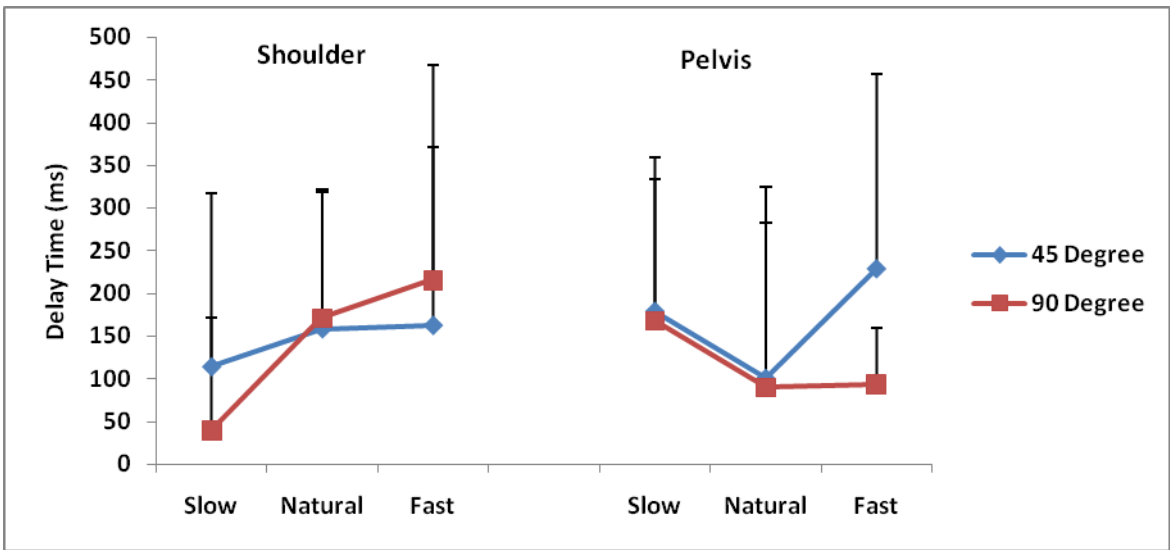


Figure 3.12. The mean and standard deviation (error bars) of the latencies of the peak angular velocity of shoulder and pelvis relative to the peak angular velocity of head at three different walking velocities during the 45° and 90° turns.

The latency of the peak angular velocity of pelvis during the 45º turns was significantly different at different walking velocities; being smallest when the participant walked at their natural speed and largest when the participant walked fast (Figure 3.12). During the 90º turns however, the latency of the peak angular velocity of pelvis was significantly larger during the slow turns in comparison with the natural speed and fast turns. The latency of the peak angular velocity of pelvis was not different between the natural speed and fast turns (Figure 3.12).

3.4 Discussion

This study examined whether healthy elderly participants show a preference for step or spin turns when changing direction while walking at different velocities. Effect of turn type (step vs. spin) on the timing and sequence of reorientation of different body segments was also investigated. Furthermore, the present study examined the effect of walking velocity on timing and sequence of reorientation of different body segments in healthy elderly.

Unlike previous studies that controlled for the turn type by instructing the participants to turn in a specific direction with a certain foot landed on the floor (Patla et al., 1999; Hollands et al., 2001), our participants were free to make a step or a spin turn. In the present study, although the starting point and the direction of the turn was specified for each trial, no instruction was given regarding with which foot participants should start their walk and/or which foot should be planted on the floor during the turn. All participants started walking from the same starting point (4 meters from the center of the turning zone). The instructions were: "Before each trial I will tell you towards which pylon you should walk. On the 'go' signal, walk straight ahead until you reach to the turning zone and then turn towards the designated pylon. You should not stop at the turning zone. Neither should you adjust your step length to step on the turning zone. The circle is there to just give you an idea that this is where about that we want you to turn." Therefore, depending on which foot the participant started to walk with, his/her step length, and where exactly he/she started his/her turn, the participant could have turned with the left or right foot planted on the floor resulting in a step or a spin turn, respectively. Since step turns are more stable and biomechanically less demanding than spin turns (Patla et al., 1991; Taylor et al., 2005), we expected that as a

safety measure our healthy elderly participants would show a preference for step turns over spin turns. Surprisingly, regardless of the magnitude and velocity of the turn our participants showed no preference in turn type. The greatest difference in prevalence of the two types of turns, although not significant, was observed as the participants made 90° turns while walking fast, with 60% of trials performed with a step turn. Patla and colleagues (1991) showed that when healthy young adults were instructed to initiate their turn with the same foot, but were free to choose their new walking direction, they showed a preference for the new walking direction. The preferred direction allowed the participants to proceed into the new direction by taking a step turn. In fact, when the available planning and execution time was limited, the step turn was the only strategy used by the limited number of healthy young adults who were able to turn successfully (Patla et al., 1991). Our healthy elderly participants however, didn't show any preference in the turn type. This is an important finding. Considering the high occurrence of turning in activities of daily living (Glaister et al., 2007), and the inherent advantages of the step turn over the spin turn (Patla et al., 1991; Taylor et al., 2005) instructions on proper turning may reduce the risk of loss of balance and fall during turning and should be included in gait retraining.

Nevertheless, the timing and sequence of reorientation of different body segments towards the new direction of travel was not different between the step and spin turns at any condition. This finding is in agreement with findings of Paquette et al. who reported no significant effect of turn type on the sequence and timing of segment reorientation for both healthy young and elderly individuals (Paquette et al., 2008).

At each level of velocity, double step turns were more common than single step turns during the larger turns (90°), i.e., participants used more preparatory steps during the 90° turns than during the 45° turns. The only condition in which the prevalence of the double step turns was significantly greater than the prevalence of the single step turns (70.2% vs. 29.8%) was when participants made 90° turns while walking fast. Fuller and colleagues showed that older adults with lower balance confidence are significantly more likely to choose a double step turn to change the direction of their travel path (Fuller et al., 2007). It is possible that the 90° turns while walking fast were most challenging for our participants; therefore, participants adopted double step turns more frequently in this condition to ensure safety. Note that the highest percentage of step turns was also observed during 90° turns while walking fast.

Regardless of the walking velocity, initiation of reorientation of different body segments in the yaw plane followed a top-down sequence starting from the head and proceeding to the shoulder, pelvis, and feet. Walking velocity had no significant effect on the delay time in initiation of reorientation of shoulder and pelvis relative to the head turn. However, delay time in initiation of mediolateral foot displacement decreased with increasing walking velocity. Walking velocity affects step length and step frequency; both step length and step frequency increase as walking velocity increases (Hirasaki et al., 1999). Decrement in delay time in mediolateral foot displacement with increasing walking velocity could be due to the increasing step frequency.

Although walking velocity had no significant effect on timing of reorientation of shoulder and pelvis relative to the head turn, it may have caused a global delay in reorientation of all

body segments. If body segments start to turn at a constant distance (rather than a constant time) to the turn point as suggested by Prévost et al. (2003), segment reorientation should initiate earliest for the slow walking velocity and latest for the fast walking velocity. Nonetheless, the present protocol does not allow examining this effect.

It is difficult to directly compare the timing of reorientation of body segments obtained in the present study with those from the previous studies since different studies have chosen different events as the reference for time zero. Furthermore, some studies have not examined the reorientation of the shoulder and pelvis separately; rather the trunk has been taken as one segment which makes the aforementioned comparison even more difficult. In the present study, averaged across different walking velocities and magnitudes of the turn, the delay times in rotation of shoulder and pelvis were 144 and 251ms, respectively. These values are smaller than what has been reported as the relative delay in trunk reorientation in healthy young adults by Patla et al. (1999) (300ms), and Grasso et al. (1998) (440 ms). Our results are closer to the results of Carpinella et al. (2007) who showed delays of 140 and 230ms for upper trunk and pelvis relative to the head as healthy elderly made a 90° left turn in the middle of their walk, and the results of Paquette et al. (2008) who reported 228ms delay in rotation of trunk as healthy elderly made a 40° turn in the middle of their walk.

At each magnitude of the turn the peak angular velocity increased as the walking velocity increased, i.e., peak angular velocity was smallest for the slow turns and largest for the fast turns. Averaged across all body segments, at each walking velocity the peak angular velocity was greater during the 90° turns than 45° turns. This result is in agreement with findings of

Grasso et al. (1996) who reported that when healthy young adults walked on a circular path the angular velocity increased as the radius of the path decreased (sharper turn).

In summary, this study showed that healthy older adults show no preference in making a step or spin turn during on-line steering. Furthermore, in healthy older adults the sequence of reorientation of body segments during on-line steering is similar to what has been reported for healthy young, i.e., rotation of body segments proceeds from the head to shoulder, pelvis, and feet. The top-down sequence in initiation of reorientation of different body segments is a robust phenomenon and does not depend on the turn type, walking velocity, and magnitude of the turn. This study showed that in healthy elderly the delay times in rotation of shoulder and pelvis relative to the head turn are smaller than what has been reported in literature for healthy young adults, indicating a more simultaneous control of head and trunk in older adults than young adults.

Chapter 4: Coordination of on-the-spot turns in individuals with Parkinson's disease "off" and "on" medication

4.1 Introduction

Postural instability is one of the cardinal symptoms of Parkinson's disease (PD) (Kandel et al., 2000). Individuals with PD could experience postural instability even in the early stages of the disease when this symptom is not easily detected by clinical examinations (Chastan et al., 2008). Postural instability of individuals with PD is exaggerated in specific circumstances such as turning (Giladi et al., 1992; Bloem et al., 2001). Report of difficulty turning is a sensitive predictor of the two key symptoms of PD locomotion: freezing and falling (Stack et al., 2006). The association of turning with falls and freezing in individuals with PD highlights the importance of understanding the turning impairment in this patient population.

A few studies provide insight on turning behavior of individuals with PD during the on-the-spot turns (Stack et al., 2006; Vaugoyeau et al., 2006; Vaugoyeau et al., 2003). Stack and colleagues (2006) examined postural performance of a group of participants with PD (Hoehn and Yahr scale II, III and IV) during 180° turns. Based on their report on the frequency of their turning difficulty, PD participants were assigned to either the difficulty turning (DT) or the no difficulty turning (NDT) group. Results showed that the DT group took more steps while turning, lacked proper heel strike more frequently, and used external support more often. Furthermore, a greater proportion of individuals with PD in the DT group than in the NDT group appeared unstable while turning.

Vaugoyeau and colleagues (2003) examined performance of PD participants in advanced stages of the disease and age-matched healthy controls while taking a 45° diagonal step with and without changing the body orientation. In both conditions, PD participants took shorter steps and produced lower amplitudes of horizontal forces than their healthy counterparts.

Furthermore, postural performance of PD participants showed greater decrements as the task complexity increased, i.e., while taking a diagonal step with change in body orientation. The authors suggested that the poor performance of individuals with PD in taking a diagonal step is due to difficulty in coordinating the two different components of the task: the whole body inclination in the forward direction, and body rotation in the direction of the step (Vaugoyeau et al., 2003). Investigating the temporal organization of body segment reorientation in the yaw plane provided further insight into the source of poor performance of PD participants. In healthy controls reorientation of body segments started with the head and was followed by simultaneous reorientation of shoulder and pelvis. PD participants however, showed a global delay in the onset of body rotation, accompanied by a significant delay between the onset of rotation of shoulders and pelvis (Vaugoyeau et al., 2006).

In the aforementioned studies PD participants were tested while "on" medication. To our knowledge the role of dopaminergic medication on turning performance of individuals with PD has not been examined yet.

The objectives of the present study are: 1) to quantify the sequence and timing of body segment reorientation in individuals with PD during on-the-spot turns; 2) to examine the possible effect of magnitude of the turn on the sequence and timing of reorientation of different body segments towards the new direction; and 3) to investigate any possible effect of dopaminergic medications on the sequence and timing of body segment reorientation in individuals with PD during the on-the-spot turns. This was achieved by testing the PD participants "off" and "on" their dopaminergic medications.

4.2 Methods

4.2.1 Participants

Fourteen individuals with Parkinson's disease, 7 males and 7 females, 57 to 74 years old (mean±std age=67±4.8 years) participated in this study. The mean and standard deviation of the PD participants' height and body mass were 169±9cm and 75±9.9kg, respectively. Nineteen healthy community-dwelling older adults, 10 males and 9 females, 60 to 75 years old (mean±std age=66±4.2 years) volunteered to participate as the control group. The mean and standard deviation of the healthy older adults' height and body mass were 170±11cm and 77±17kg, respectively.

All individuals with Parkinson's disease were diagnosed with idiopathic PD by their neurologist. PD participants were either referred by their neurologist or were recruited from the local Parkinson's disease support groups. PD participants were free from any significant orthopedic (e.g. fracture or severe osteoarthritis) or additional neurologic (e.g. stroke or traumatic brain injury) conditions. Individuals with PD who were not able to walk continuously for a distance of 100m (one city block) without assistance (i.e., cane or walker), or were not able to follow simple commands were excluded from the study.

Healthy elderly were recruited through the University of Waterloo Research in Ageing Participant Pool (WRAP). Healthy older adults were free from any neurological, musculoskeletal or vestibular impairment, and had no history of falls in the six months prior to the experiment as verified by self-report.

All participants were informed about the experimental procedure before signing a consent form. All procedures were approved by the Office of Research Ethics at the University of Waterloo and the University of Western Ontario.

4.2.2 Procedure

For all participants information regarding participants' age, height, and medical history were collected. Participants' cognitive status was determined using the Modified Mini Mental Test (Teng and Chui, 1987). This test has a total possible score of 100 points; a score of less than 80 has been suggested as a criterion for cognitive impairment. Participants' trait anxiety level was examined using the Beck Anxiety Inventory scale (Beck et al., 1988). This scale consists of 21 items, each describing a common symptom of anxiety with a total possible score of 0 to 63 points. A total score of less than 21, 22-35, and greater than 36 is considered an indication of very low, moderate, and severe anxiety, respectively. No difference was found between the two groups in terms of anthropometric measures (age, height, and weight), Modified Mini Mental Test score, and BAI score. However, as expected the number of medications was significantly greater for PD participants than for healthy elderly ($t=-3.87$, $P=0.0005$). Mean and standard deviation of the number of medication was 4.4 ± 2.6 and 1.5 ± 1.6 for PD participants and healthy participants, respectively. This information is summarized in Table 4.1.

The participants' functional mobility was tested using the Timed-Up-and-Go (TUG) test and the 7m self-paced walking test. These tests have been shown to be both reliable and valid estimates of functional mobility (Podsiadlo and Richardson, 1991; Shumway-Cook et al.,

PD participants' ID	Gender	Age (year)	Height (cm)	Body Mass (kg)	3MS Score	BAI Score	TUG (s) ("off" Med)	TUG (s) ("on" Med)	Self-Paced (m/s) ("off" Med)	Self-Paced (m/s) ("on" Med)	# of Medications
1	F	64	165	64	96	1	10.4	9.4	0.66	0.88	3
2	F	57	170	77	95	15	11.8	12.6	0.88	0.97	3
3	M	70	168	68	97	2	9.3	9.2	1.07	1.08	3
4	F	64	152	73	96	8	11.7	9.2	0.83	1.3	8
5	M	67	178	84	89	2	10.6	11.1	0.91	1.02	9
6	M	70	185	91	100	1	9.7	9.6	0.83	0.89	2
7	F	68	160	83	95	0	10.5	9.8	1	1.05	5
8	M	62	165	80	99	4	10	7.7	1.05	1.24	3
9	F	70	163	62	97	25	8.1	9.8	1.1	1.1	2
10	M	73	175	77	97	13	9.9	10.3	1.07	0.96	5
11	M	62	185	63	98	20	13.2	11.5	1.11	1.09	4
12	M	63	173	91	98	4	11.6	11.5	0.96	0.98	1
13	F	70	165	71	97	23	9.9	11.6	0.82	1	9
14	F	74	165	66	93	17	9.2	9.4	1.16	1.2	4
Mean		67	169	75	96	9.6	10.4*	10.2*	0.96^{Ω}	1.05	4.4*
Std		4.8	9.3	9.9	2.7	8.9	1.3	1.3	0.14	0.13	2.6

Healthy Participants (n=19, 10 M, 9 F)	**Age (year)**	**Height (cm)**	**Body Mass (kg)**	**3MS Score**	**BAI Score**	**TUG (s)**	**Self-Paced (m/s)**	**# of Medications**
Mean	66	170	77	97	5	8.8	1.02	1.5
Std	4.2	11.4	17	3.6	3.4	1.0	0.15	1.6

Table 4.1. Characteristics of the PD participants (n=14) and healthy elderly (n=19). 3MS: Modified Mini-Mental State; BAI: Beck Anxiety Inventory; TUG: Timed-Up-and-Go score (s); Self-Paced: 7m self-paced walking speed (m/s). Stars indicate significant difference from comparable value for healthy participants (P<0.05, unpaired t-test). $^{\Omega}$ indicates significant difference between OFF and ON medication (P<0.05, paired t-test).

1997). The TUG was administered by observing and timing the participant rising from a chair, walking three meters, turning 180°, walking back to the chair and sitting down (Podsiadlo and Richardson, 1991). For each participant, three trials of the TUG were completed and the best score was recorded. The 7m self-paced walking test was also performed three times and the participant's best score was recorded (Table 4.1).

For PD participants, duration of Parkinson's disease (time since diagnosis) and the type and daily dose of their anti-parkinsonian medication were recorded. Clinical assessment of motor disability was performed using the motor component of the Unified Parkinson's Disease Rating Scale (UPDRS) (Fahn and Elton, 1987) when participants were "off" and "on" medication. This information is summarized in Table 4.2. Number of falls in the six months prior to testing was also recorded. Three participants reported one fall during the six months prior to testing.

Participants were asked to change into tight-fitting clothing. Fourteen infra-red emitting diodes (IREDs) were mounted on fourteen anatomical landmarks of the participants' body to track the movements of their body. Twelve IREDs were mounted on the following anatomical landmarks bilaterally: ear, shoulder joint, anterior superior iliac spine, hip joint, lateral malleolus, and the big toe. One IRED was mounted on the chin and another IRED was placed on the participants' chest approximately 5cm below the jugular notch.

Participants stood on the lab floor with their arms crossed in front of their chest. Four pylons were placed approximately 3m away from them at 45° and 90° to their right and left. Before each trial the direction and magnitude of the turn was specified, i.e., participants were told

PD participant's ID	Duration of Disease[§]	Parkinsonian Medication	Daily Dose of Dopaminergic Medications (Levodopa Equivalents[Δ]) in milligram	UPDRS Score "Off" Med	UPDRS Score "On" Med
1	5	Pramipexole	201	30.5	16
2	4	Levodopa/Carbidopa, Trihexyphenidyl	400	38	32.5
3	9	Levodopa/Carbidopa	450	39	23.5
4	5	Levodopa/Carbidopa	500	22	12.5
5	6	Levodopa/Carbidopa	800	36	24
6	2	Rasagiline	1mg per day[Ω]	20.5	12
7	7	Ropinirole	200.04	13.5	6.5
8	5	Levodopa/Carbidopa & Pramipexole	401.5	14.5	6
9	8	Levodopa/Carbidopa	450	12	12
10	1	Rasagiline	1mg per day[Ω]	18	9.5
11	8	Levodopa/Carbidopa	1000	29	20.5
12	3	Levodopa/Carbidopa	400	19.5	12
13	5	Levodopa/Carbidopa & Ropinirole	733.36	14	8
14	4	Levodopa/Carbidopa	600	25	22
Mean	5			24*	16
Std	2.3			9.4	7.8

Table 4.2. Parkinson patients (n=14). [§]Duration of Disease: years since diagnosis; UPDRS: Unified Parkinson's Disease Rating Scale; * indicates significant difference between PD "off" and "on" medication (P<0.05, paired t-test). [Δ] Calculated based on the formula by Hobson et al., 2002. [Ω] Rasagiline is a new medication, and currently there is no formula for calculating the levodopa equivalent of this medication.

which pylon they should turn toward. For each trial, participants were instructed to turn (on the "go" signal) with their whole body to face the designated pylon.

Each participant performed three trials of on-the-spot turns towards each direction for a total of 12 trials. However, data were collected only during the trials that participants made a right turn (6 trials). Participants were unaware that data were not being collected during the left-turn trials. The order of the right-turn and left-turn trials was completely randomized.

Upon completion of all the trials, participants' spinal flexibility was measured using the Functional Axial Rotation (FAR) test (Schenkman et al., 2001). Participants were asked to sit on a stool with their feet flat on the floor and their arms resting on their lap. Participants were instructed to turn their head and trunk to their right and then left as far as they could to look at the wall behind them without lifting their feet from the floor or rising from the stool. Movements of the head and trunk were recorded using the Optotrak cameras. Angular displacements of the head and shoulders in the yaw plane were calculated using the Optotrak data. These measures indicate the flexibility of the cervico-thoraco-lumbar and thoraco-lumbar spine. This information is summarized in Table 4.3.

PD participants (n=14)	FAR Head ("off" Med)	FAR Shoulder ("off" Med)	FAR Head ("on" Med)	FAR Shoulder ("on" Med)
Mean	93.8	36.4	91	35.6
Std	14.9	9.7	16	11.6
Healthy Participants(n=19)	**FAR Head**	**FAR Shoulder**		
Mean	99.5	42.8		
Std	13.4	10.2		

Table 4.3. Functional Axial Rotation score (FAR) for PD participants "off" and "on" medication and healthy controls. Scores shown are the average of the scores for the right and left sides.

PD participants were tested both "off" and "on" dopaminergic medication. They were asked to skip the last dose of their anti-parkinsonian medication prior to coming to the laboratory. Upon arrival, they were tested while they were "off" dopaminergic medications. After completion of the "off medication" testing, PD participants were asked to take their dopaminergic medication. The second round of the experiment started when the participant reported that he/she is in his/her "on medication" state (about an hour after taking the medication). For PD participants the Functional Axial Rotation (FAR) test was performed in both "off" and "on" medication conditions (Table 4.3).

Rest periods were provided throughout the experiment upon the participants' request. Throughout the experimental trials, movements of the participants' body were videotaped.

4.2.3 Data collection

Two horizontal and two vertical Optotrak 3D imaging system cameras (Northern Digital Inc., Canada) were used to collect kinematic data. The horizontal cameras were positioned on top of one another and were placed in front of the participant. The vertical cameras were positioned at the participant's right side. Optotrak data were recorded at 120 Hz.

4.2.4 Data processing

The Optotrak data were low-pass filtered (Butterworth) prior to analyses with a cut-off frequency of 6 Hz. The yaw angular displacement profiles of the head, shoulder (upper trunk), and pelvis in the global reference frame were determined from the three non-co-linear markers placed on each of the aforementioned segments. The three markers define the rigid body of each segment, making it possible to determine its orientation with respect to the gravito-inertial frame.

For each trial, data collection started at least one second before the participant was instructed to turn. The initiation of reorientation of head, shoulder, and pelvis was calculated as the point in time that the angular displacement data indicated the start of the turn towards the new direction providing the deviation continued beyond the quiet stance range.

Toe displacement profiles were used to determine the onset of change in the mediolateral foot displacement towards the new direction. The onset of foot mediolateral deviation was calculated as the point in time that the test data deviated towards the designated direction providing the deviation continued beyond the quiet stance range.

The time at which head reorientation towards the new direction initiated was considered the reference time (time = 0 ms). DT-Shoulder, DT-Pelvis and DT-First Step refer to the delay time (DT) for reorientation of shoulder, pelvis, and the foot that deviated first towards the new direction (respectively) in the yaw plane relative to the aforementioned reference time.

For each trial the peak angular velocity of head, shoulder and pelvis in the yaw direction after the onset of the segment's movement was calculated. The time at which head reached its peak angular velocity in the yaw direction was considered the reference time (time = 0 ms). The latencies of the peak angular velocity of shoulder and pelvis relative to this reference time were computed.

For each trial, the magnitude of head, shoulder and pelvis turn in a window of time defined by the time that the segment initiated its reorientation and the onset time of the mediolateral foot displacement was calculated.

4.2.5 Data Analysis

4.2.5.1 Effects of Parkinson's disease on the coordination of reorientation of different body segments during the on-the-spot turns

Data collected from the healthy elderly participants and PD participants while "off" medication were used to examine the effects of Parkinson's disease on the coordination of reorientation of different body segments during the on-the-spot turns. In the original analyses, gender was included as a factor. However, results revealed no significant main effect of gender on the timing and sequence of body segment reorientation and angular velocity values. The only significant interaction effect of gender was the group*gender*segment*magnitude interaction effect on the peak angular velocity values. Considering that gender had no significant main effect on the timing and sequence of body segment reorientation and angular velocity values, and given the small number of participants in each gender group we removed the gender factor to preserve the power of the analyses.

To examine the effect of Parkinson's disease on the sequence and timing of reorientation of different body segments, and to explore the effect of magnitude of the turn on the aforementioned sequence and timing a three way repeated measure ANOVA with group (healthy vs. PD) as between factor and body segment (shoulder, pelvis, foot), and magnitude of the turn (45°, 90°) as within factors was performed on the delay times (DTs) in the initiation of reorientation of different body segments relative to the initiation of reorientation of the head. Since the initiation of reorientation of head is considered as the reference time (time = 0), head could not be included as a segment in the above analysis. Therefore, one-way t-tests were performed to determine if the means of the delay times in the initiation of reorientation of

shoulder, pelvis and foot are significantly different from zero (initiation of head reorientation). A Bonferroni correction was used to correct for multiple comparisons.

To compare the peak angular velocity of different body segments between healthy and PD participants and to examine the effect of magnitude of the turn on the peak angular velocities, a three way repeated measure ANOVA with group (healthy vs. PD) as between factor and body segment (head, shoulder, pelvis), and magnitude of the turn (45°, 90°) as within factors was performed on the peak angular velocities of the head, shoulder and pelvis.

To examine the effect of Parkinson's disease on the sequence and timing of the peak angular velocity of different body segments during the on-the-spot turns and to explore the effect of magnitude of the turn on the aforementioned sequence and timing, a three way repeated measure ANOVA with group (healthy vs. PD) as between factor and body segment (shoulder, pelvis), and magnitude of the turn (45°, 90°) as within factors was performed on the latencies of the peak angular velocity of shoulder and pelvis relative to the peak angular velocity of the head.

To examine the effect of Parkinson's disease on the amount of turn achieved by different body segments at the onset of mediolateral foot displacement during small and large turns, a three way repeated measure ANOVA with group (healthy vs. PD) as between factor and body segment (head, shoulder, pelvis), and magnitude of the turn (45°, 90°) as within factors was performed on the amount of turn at the onset of mediolateral foot displacement.

4.2.5.2 Effects of dopaminergic medications on the coordination of reorientation of different body segments during the on-the-spot turns in individuals with Parkinson's disease

Data obtained from PD participants while "off" and "on" medication were analyzed to examine any possible effect of dopaminergic medications on the coordination of reorientation of different

body segments during the on-the-spot turns. In the original analyses gender was included as a factor. However, results revealed no significant main effect of gender. The only significant effect of gender was the gender*segment interaction effect on the timing of reorientation and the peak angular velocity of different body segments. Considering that gender had no significant main effect on any of the variables of interest, and given the small number of participants in each gender group we removed the gender factor to preserve the power of the analyses.

To examine the effect of dopaminergic medication on the sequence and timing of reorientation of different body segments, and to explore the effect of magnitude of the turn on the aforementioned sequence and timing, a three way repeated measure ANOVA with medication condition ("off" and "on"), body segment (shoulder, pelvis, foot), and magnitude of the turn (45°, 90°) as within factors was performed on the delay times in the initiation of reorientation of different body segments relative to the initiation of reorientation of the head. Since the initiation of reorientation of head is considered as the reference time (time = 0), head could not be included as a segment in the above analysis. Therefore, one-way t-tests were performed to determine if the means of the delay times in the initiation of reorientation of shoulder, pelvis and foot are significantly different from zero (initiation of head reorientation). A Bonferroni correction was used to correct for multiple comparisons.

To examine the effect of dopaminergic medication on the peak angular velocity of different body segments and to explore the effect of magnitude of the turn on the peak angular velocities a three way repeated measure ANOVA with medication condition ("off" and "on"), body segment (head, shoulder, pelvis), and magnitude of the turn (45°, 90°) as within factors was performed on the peak angular velocities of different body segments.

To examine the effect of dopaminergic medications on the sequence and timing of the peak angular velocity of different body segments and to explore the effect of magnitude of the turn on the aforementioned sequence and timing a three way repeated measure ANOVA with medication condition ("off" and "on"), body segment (shoulder, pelvis), and magnitude of the turn (45°, 90°) as within factors was performed on the latencies of the peak angular velocity of shoulder and pelvis relative to the peak angular velocity of the head.

To examine the effect of dopaminergic medications and magnitude of the turn on the amount of turn achieved by the onset of mediolateral foot displacement, a three way repeated measure ANOVA with medication condition ("off" and "on"), body segment (head, shoulder, pelvis), and magnitude of the turn (45°, 90°) as within factors was performed on the amount of turn at the onset of mediolateral foot displacement.

In conditions that a main or interaction effect of a factor was revealed, Tukey's Studentized Range (HSD) Test was performed to determine which means were significantly different from the others. For all tests, a significance value (P) of less than 0.05 was used to test statistical significance.

4.3 Results

4.3.1 Effects of Parkinson's disease on the coordination of reorientation of different body segments during the on-the-spot turns

4.3.1.1 Sequence and timing

Results of the three way ANOVA revealed significant effects of segment ($F(2,62)=336.70$, $P<0.0001$), magnitude of the turn ($F(1,31)=6.16$, $P=0.0187$), and segment*magnitude ($F(2,62)=3.74$, $P=0.0293$) on the delay times in the initiation of reorientation of different body

segments relative to the initiation of reorientation of the head. Further examination revealed that during the on-the-spot turns regardless of the magnitude of the turn, both healthy older adults and participants with Parkinson's disease turned their shoulder and pelvis in unison. Furthermore, results of the one-way t-tests revealed that DT-shoulder and DT-pelvis were not different from zero (i.e., the onset of head rotation) for both groups and for both magnitudes of turn. However, DT-first step was significantly different from zero for both groups. These results indicate that during the on-the-spot turns, regardless of the magnitude of the turn, both healthy elderly and PD participants turned their head, shoulder, and pelvis simultaneously. The simultaneous reorientation of the head and trunk in the yaw plane was followed by reorientation of the feet (Figure 4.1).

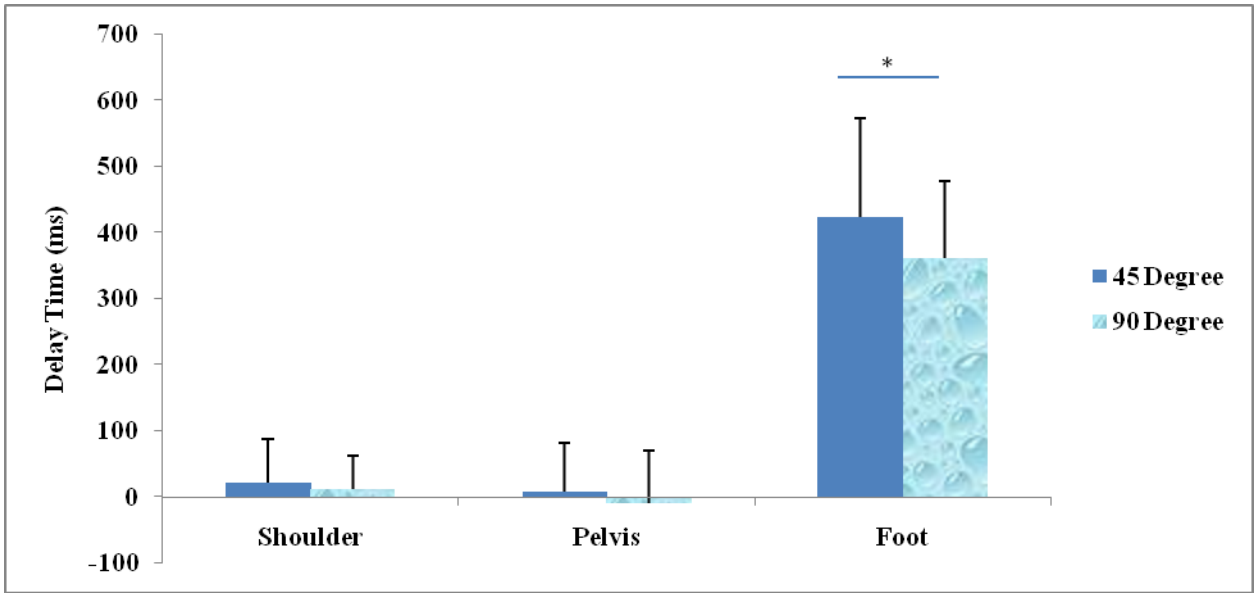


Figure 4.1. Mean and standard deviation (error bars) of the delay times in the initiation of reorientation of shoulder, pelvis and foot in yaw plane relative to the initiation of head reorientation during the on-the-spot turns at two different magnitudes of turn averaged across all participants. Star indicates significant difference (α=0.05).

Furthermore, Tukey's analyses revealed that the delay time in initiation of reorientation of foot was significantly longer during the 45° turns than the 90° turns (mean±std=424±150 and 361±118ms for 45° and 90° turns, respectively). Parkinson's disease had no significant main or interaction effect on the sequence and timing of the reorientation of different body segments.

4.3.1.2 Velocity

ANOVA revealed significant main effect of group ($F(1,31)=10.86$, $P=0.0025$), segment ($F(2,62)=45.59$, $P<0.0001$), and magnitude of the turn ($F(1,31)=284.20$, $P<0.0001$) on the peak angular velocities of head, shoulder and pelvis. Segment*group ($F(2,62)=8.36$, $P=0.0006$), and segment*magnitude ($F(2,62)=34.49$, $P<0.0001$) interaction effects were also significant. Examining the segment*group interaction revealed that for all body segments the peak angular velocity was significantly smaller for PD participants than healthy elderly (Figure 4.2). Mean and standard deviation of the peak angular velocity of head, shoulder, and pelvis were 69.3±25.8, 59.9±16.9, and 62.9±18.1deg/s for PD participants, and 97.5±35.8, 80±28.9, and 78.1±25.5deg/s for healthy elderly, respectively. Furthermore, for each group of participants the peak angular velocity of head was significantly greater than the peak angular velocity of shoulder and pelvis (Figure 4.2). The peak angular velocity of shoulder and pelvis were not different from each other for either group.

Examining the segment*magnitude interaction effect revealed that for all body segments the peak angular velocity was significantly greater during the 90° turns than during the 45° turns (Figure 4.3). Mean and standard deviation of the peak angular velocity of head, shoulder, and pelvis were 108.9±30.8, 85.3±26, and 84.9±22.4deg/s during the 90° turns, and 62.2±19.1, 57.6±18.4, and 58.8±17.3deg/s during the 45° turns, respectively (Figure 4.3). Furthermore, while there was no significant difference in the peak angular velocity of head, shoulder, and

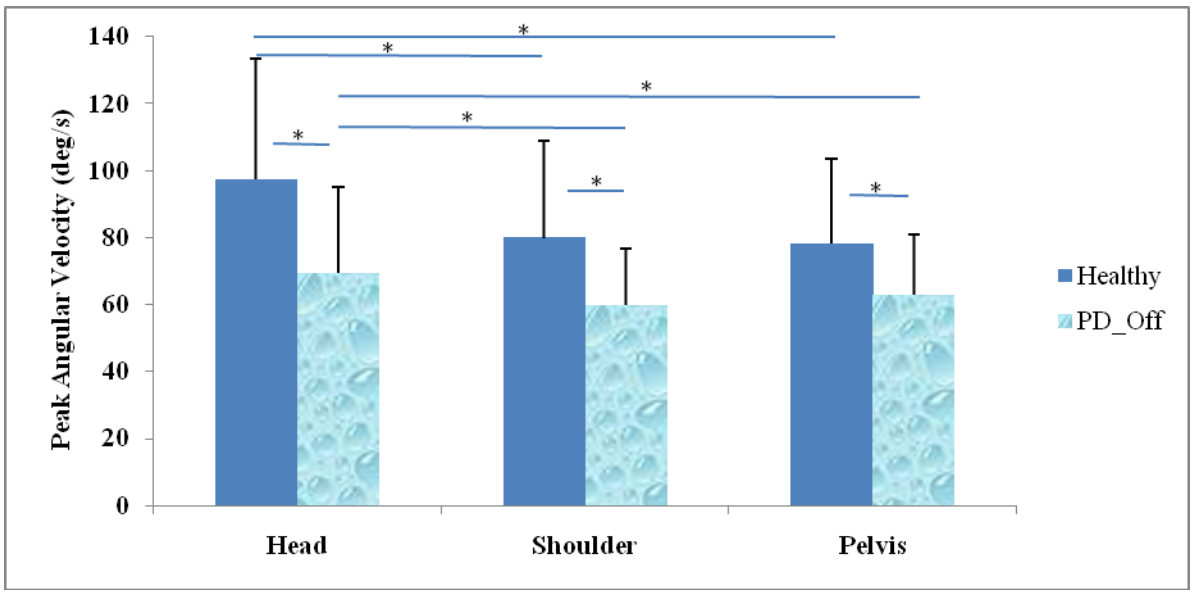


Figure 4.2. Mean and standard deviation (error bars) of the peak angular velocity of head, shoulder, and pelvis in yaw plane during the on-the-spot turns for healthy elderly and PD participants "off" medication averaged across the two different magnitudes of turn. Stars indicate significant differences (α=0.05).

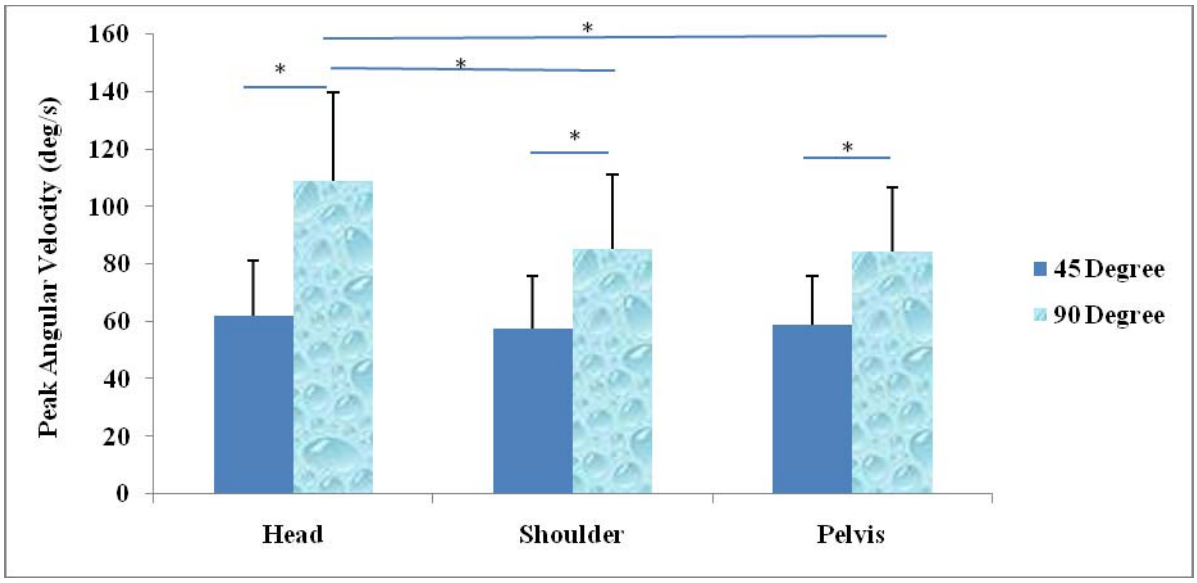


Figure 4.3. Mean and standard deviation (error bars) of the peak angular velocity of head, shoulder, and pelvis in yaw plane during the 45° and 90° on-the-spot turns averaged across all participants. Stars indicate significant differences (α=0.05).

pelvis during the 45° turns, the peak angular velocity of head was significantly greater than the peak angular velocity of shoulder and pelvis during the 90° turn (Figure 4.3).

ANOVA revealed significant interaction effect of segment*magnitude of the turn ($F(1,31)=13.52$, $P=0.0009$) on the latencies of the peak angular velocity of shoulder and pelvis relative to the peak angular velocity of the head. Tukey's analyses revealed that while the latency of the peak angular velocity of shoulder remained unchanged during the 45° and 90° turns (mean±std=144±156 and 140±151ms, respectively), the latency of the peak angular velocity of pelvis was significantly shorter during the 45° turns than the 90° turns (mean±std=84±133, 207±200ms, respectively) (Figure 4.4).

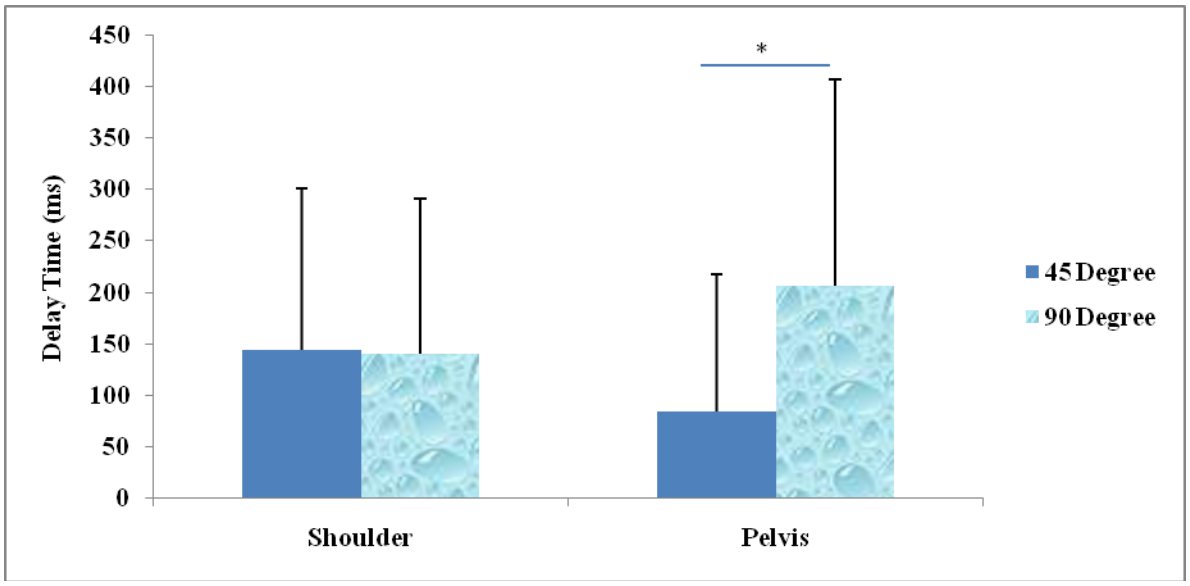


Figure 4.4. Mean and standard deviation (error bars) of the latencies of the peak angular velocity of shoulder and pelvis relative to the peak angular velocity of the head during the on-the-spot turns at two different magnitudes of turn averaged across all participants. Star indicates significant differences (α=0.05).

4.3.1.3 Magnitude

The three way ANOVA revealed significant effect of group ($F(1,31)=8.13$, $P=0.0077$), segment ($F(2,62)=57.02$, $P<0.0001$), and group*segment ($F(2,62)=4.76$, $P=0.0119$) on the amount of turn achieved by the onset of mediolateral foot displacement. Tukey's analyses revealed that the amount of turn achieved by each body segment by the onset of mediolateral foot displacement was significantly smaller for PD participants than for healthy controls (mean±std=10.9±3.8 and 16.3±6.9deg for head, 7.3±2.5 and 11.1±5.1deg for shoulder, and 7.8±2.9 and 10.2±4.9 for pelvis for PD participants and healthy elderly, respectively) (Figure 4.5). For both groups the amount of head turn was significantly greater than the amount of shoulder and pelvis turn. The amount of head turn in PD participants was significantly smaller than the amount of head turn in healthy elderly, and was similar to the amount of shoulder and pelvis turn of healthy older adults (Figure 4.5).

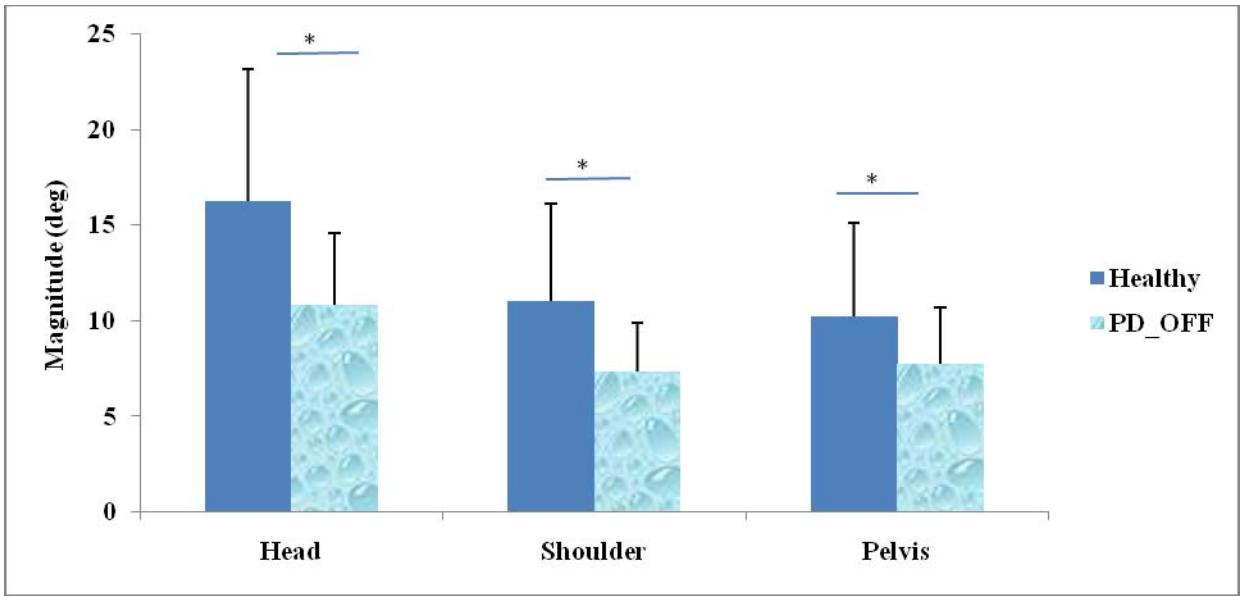


Figure 4.5. Mean and standard deviation (error bars) of the magnitude of head, shoulder, and pelvis turn at the onset of mediolateral displacement of the leading foot for healthy elderly and PD participants "off" medication averaged across the two different magnitudes of the turn. Stars indicate significant differences (α=0.05).

4.3.2 Effects of dopaminergic medications on the coordination of reorientation of different body segments during the on-the-spot turns in individuals with Parkinson's disease

4.3.2.1 Sequence and timing

Results of the three way repeated measure ANOVA revealed only significant main effect of segment ($F(2,26)=117.89$, $P<0.0001$) on the latencies of the initiation of reorientation of different body segments relative to the initiation of reorientation of the head (DTs). Tukey's analyses revealed that in PD participants, regardless of the medication condition and magnitude of the turn, the delay time in initiation of foot reorientation was significantly longer than DT-shoulder and DT-pelvis (mean±std=29±57, 29±67, and 417±159ms for DT-shoulder, DT-pelvis, and DT-first step, respectively).

Results of the one-way t-tests revealed that while "off" medication, DT-shoulder and DT-pelvis were not different from zero during both 45° and 90° turns (Figure 4.6). While "on" medication however, DT-shoulder during 45° turns ($t=3.81$, $P=0.0022$), and DT-pelvis during 90° turns ($t=3.30$, $P=0.0057$) were significantly different from zero (Figure 4.6). During both "off" and "on" medication and for both magnitudes of the turn, DT-first step was significantly different from zero (Figure 4.6). These results indicate that while "off" medication, regardless of magnitude of the turn, PD participants turned their head, shoulder, and pelvis simultaneously. The simultaneous reorientation of the head and trunk in the yaw plane was followed by reorientation of the feet. While "on" medication, segment reorientation during 45° turns started by simultaneous rotation of head and pelvis, followed by rotation of shoulder, and lastly the feet. For PD participants "on" medication, mean and standard deviation of DT-shoulder, DT-pelvis, and DT-first step during 45° on-the-spot turns were 51±50, 45±89, and 393±151ms, respectively (Figure 4.6). Segment reorientation during 90° turns while "on" medication started by

simultaneous rotation of head and shoulder, followed by rotation of pelvis, and lastly the feet. For PD participants "on" medication, mean and standard deviation of DT-shoulder, DT-pelvis, and DT-first step during 90° on-the-spot turns were 31±46, 42±48, and 399±176ms, respectively (Figure 4.6).

4.3.2.2 Velocity

Results of the three way repeated measure ANOVA revealed significant effects of segment ($F(2,26)=26.24$, $P<0.0001$) and magnitude of the turn ($F(1,13)=197.99$, $P<0.0001$) on the peak angular velocities of different body segments. Segment*magnitude interaction effect was also significant ($F(2,26)=29.69$, $P<0.0001$). For all body segments the peak angular velocity was significantly greater during the 90° turns than during the 45° turns (Figure 4.7). Mean and standard deviation of the peak angular velocity of head, shoulder, and pelvis were 98.3±26.7, 75.1±16.5, and 77.7±16.8deg/s during the 90° turns, and 53.2±16.2, 50.6±12.1, and 55±14.4deg/s during the 45° turns, respectively (Figure 4.7). Examining the segment*magnitude interaction effect revealed that while there was no significant difference in the peak angular velocity of head, shoulder, and pelvis during the 45° turns; during the 90° turns the peak angular velocity of head was significantly greater than the peak angular velocity of shoulder and pelvis (Figure 4.7). Medication condition had no significant main or interaction effect on the peak angular velocities of different body segments during the on-the-spot turns.

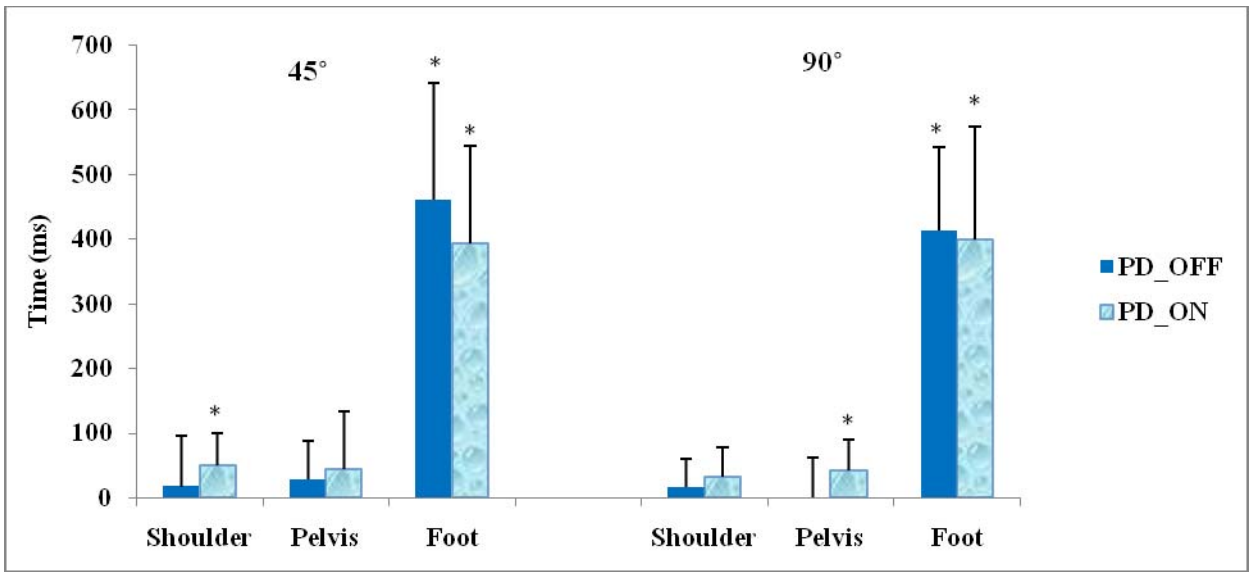


Figure 4.6. Mean and standard deviation (error bars) of the delay times in the initiation of reorientation of shoulder, pelvis and foot in yaw plane relative to the initiation of head reorientation at two different magnitudes of on-the-spot turns for PD participants "off" and "on" medication. Stars indicate significant difference from zero (α=0.008).

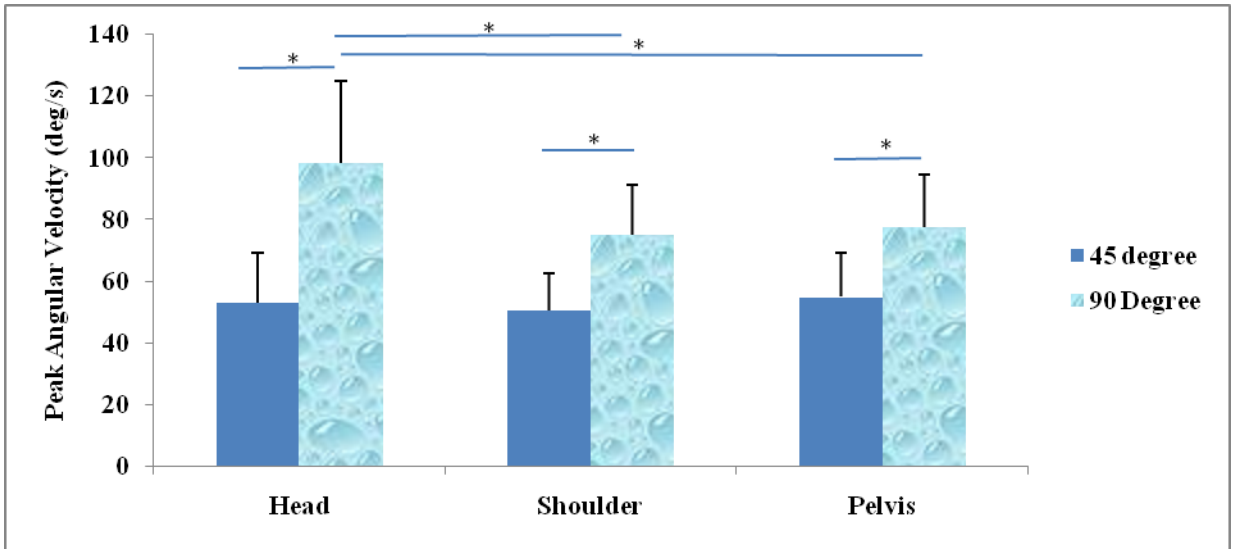


Figure 4.7. Mean and standard deviation (error bars) of the peak angular velocity of head, shoulder, and pelvis in yaw plane during the 45° and 90° on-the-spot turns for PD participants averaged across "on" and "off" medication conditions. Stars indicate significant differences (α=0.05).

The three way repeated measure ANOVA revealed significant effects of medication condition ($F(1,13)=5.12$, $P=0.0414$) and magnitude of the turn ($F(1,13)=4.81$, $P=0.0471$) on the sequence and timing of the peak angular velocity of different body segments. Segment*magnitude interaction effect was also significant ($F(1,13)=7.34$, $P=0.0179$). Tukey's analysis revealed that averaged across all body segments and magnitudes of the turn, the latency of the peak angular velocity was significantly larger when PD participants were "on" medication than when they were "off" medication (mean±std=225±292 vs. 140±160ms for "on" and "off" medication, respectively).

Examining the segment*magnitude interaction effect revealed that the latencies of the peak angular velocity of shoulder and pelvis were significantly longer during the 90° turns than during the 45° turns. Mean and standard deviation of the latencies of the peak angular velocity of shoulder and pelvis were 230±278 and 268±338ms during the 90° turns, and 142±113 and 90±98ms during the 45° turns, respectively (Figure 4.8). Furthermore, while during the 45° turns the latency of the peak angular velocity of shoulder was significantly longer than the latency of the peak angular velocity of pelvis, there was no significant difference in the aforementioned measures during the 90° turns (Figure 4.8).

4.3.2.3 Magnitude

The three way ANOVA revealed significant effect of segment ($F(2,26)=37.51$, $P<0.0001$), segment *medication condition ($F(2,26)=3.95$, $P=0.0318$), segment*magnitude of the turn ($F(2,26)=4.59$, $P=0.0196$), and segment*medication condition*magnitude of the turn ($F(2,26)=4.76$, $P=0.0173$) on the amount of turn achieved by the onset of mediolateral foot displacement. Further analyses revealed that only during the 90° turns and only for the head the magnitude of turn was significantly greater for PD participants while "on" medication than "off"

medication. Mean and standard deviation of the amount of head turn at the onset of mediolateral foot displacement was 14.5±7.9 and 10.9±4.5deg for PD participants "on" and "off" medication, respectively (Figure 4.9).

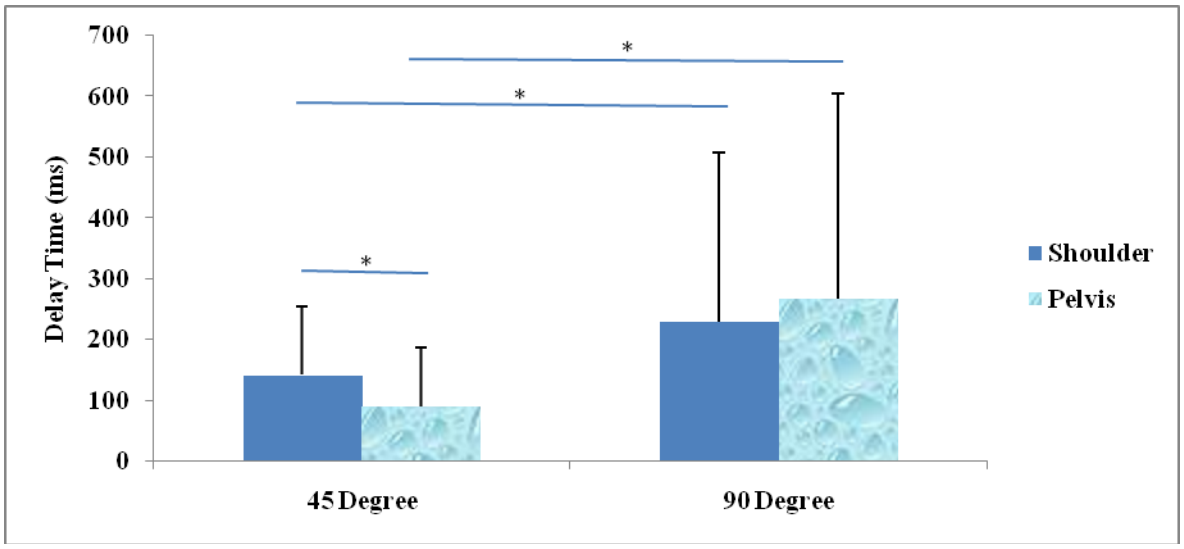


Figure 4.8. Mean and standard deviation (error bars) of the latencies of the peak angular velocity of shoulder and pelvis relative to the peak angular velocity of the head during the on-the-spot turns at two different magnitudes of turn for PD participants averaged across "on" and "off" medication conditions. Stars indicate significant differences (α=0.05).

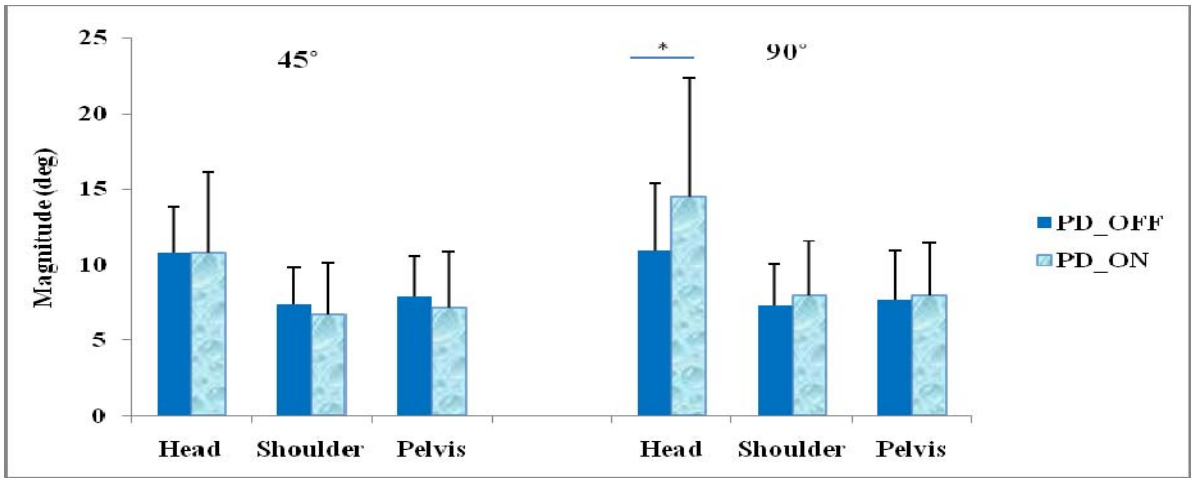


Figure 4.9. Mean and standard deviation (error bars) of the amount of head, shoulder, and pelvis turn for PD participants "off" and "on" medication at the two different magnitudes of the turn. Star indicates significant difference (α=0.05).

4.3.2.4 Functional Axial Rotation

Analyses of the Functional Axial Rotation scores revealed no difference in the flexibility of the cervico-thoraco-lumbar and thoraco-lumbar spine of the healthy controls and PD participants. Furthermore, FAR score was not different between PD participants "off" and "on" medication. Mean and standard deviation of the FAR score for healthy participants and PD participants "off" and "on" medication was: 99.5±13.4, 93.8±14.9, and 91±16deg for the cervico-thoraco-lumbar spine, and 42.8±10.2, 36.4±9.7, and 35.6±11.6deg for thoraco-lumbar spine, respectively.

4.4 Discussion

This study examined the coordination of body segment reorientation in individuals with Parkinson's disease during on-the-spot turns. The coordination of body segments was examined for small and large turns. PD participants were examined when "off" and "on" dopamine-replacement medication to determine the effects of medication on multi-segmental coordination when turning.

Coordination patterns were similar for PD participants and healthy age-matched older adults. Regardless of the magnitude of the turn, both groups turned their head, shoulder and pelvis in unison. The simultaneous reorientation of the head and trunk in the yaw plane was followed by reorientation of the feet. It should be noted that while the relative timing of reorientation of different body segments was not impaired in our sample of PD participants, PD may have caused a global delay in reorientation of all body segments; however, the present protocol does not allow examining the possibility of a global delay.

This study was the first to examine the coordination of body segment reorientation in individuals with Parkinson's disease during on-the-spot turns. A study by Vaugoyeau and colleagues (2006) provides some insight on segment orientation during on-the-spot turns in individuals with PD.

Our results differ from the reports by Vaugoyeau et al. that indicate a significant delay between the onset of rotation of shoulders and pelvis as individuals with PD make a 45° diagonal step while changing their body orientation. The different findings of our study could be due to the differences in the methodology. Participants in Vaugoyeau and colleagues' study were instructed to take a step as they turned. Our participants were not required to take a step; they were simply instructed to turn while standing on the same spot. It should be noted that findings of Vaugoyeau et al. were different from our findings even for reorientation of body segments in healthy elderly.

Dopaminergic medications had limited effect on the sequence and timing of body segment reorientation and this effect depended on the magnitude of the turn. During the 45° turns, dopaminergic medications resulted in a significant delay in rotation of shoulder, but not pelvis. Turning started by simultaneous rotation of head and pelvis, followed by rotation of shoulder, and lastly the mediolateral foot displacement. Closer examination of the mean and standard deviation of latencies of shoulder and pelvis explains this rather surprising finding. While the difference in the average latencies of shoulder and pelvis turn was only 6ms, the standard deviation of the latencies of shoulder was much smaller than the comparable value for pelvis (50 vs. 89ms).

During the 90° turns, dopaminergic medications delayed the initiation of reorientation of shoulder and to a greater extent pelvis. Therefore, turning started with simultaneous reorientation of head and shoulder, followed by pelvis and lastly the mediolateral displacement of the leading foot.

Regardless of the medication condition, the peak angular velocity of all body segments was significantly smaller for the PD participants than the healthy elderly. This finding complements

recent findings by Visser et al. (2007) who reported lower trunk peak yaw and roll angular velocities for individuals with PD in comparison with age-matched healthy controls during different walking turns: turning while walking at self-selected pace, turning while walking as fast as possible, turning suddenly upon an auditory cue, and turning while engaged in a secondary cognitive task. The lower peak angular velocities in individuals with PD could be due to bradykinesia. Alternatively, slower turns may be a compensatory strategy; individuals with PD may turn slower to produce less body angular momentum to be arrested at the end of the turn.

Examining the magnitude of the turn of different body segments at the onset of mediolateral foot displacement revealed further differences between performance of healthy elderly and PD participants; for each segment the amount of turn was significantly smaller for PD participants "off" medication than for healthy elderly. Contrary to the reports of diminished spinal flexibility in individuals with PD (Bridgewater et al., 1998; Schenkman et al., 2000; Schenkman et al., 2001), in our study functional axial rotation scores of PD participants were not different from those of the healthy controls. Even while "off" medication, our PD participants' spinal flexibility was similar to that of the healthy controls, suggesting that mechanical deficits are not responsible for the reduced magnitude of the turn in our participants. The smaller amount of turn achieved by PD participants could be due to their lower angular velocity. Alternatively, smaller turns could be the direct result of PD. The role of basal ganglia in scaling the amplitude of movement is well documented (Kandel et al., 2000; Desmurget et al., 2004; Morris et al., 2005). Although medication increased the magnitude of the head turn during the 90° turns, the magnitude of the head turn in PD participants "on" medication was still smaller than the comparable value for healthy controls (mean±std=14.5±7.9 and 17.2±7.5deg for PD participants "on" medication and healthy controls, respectively).

Chapter 5: Coordination of turning while walking in individuals with Parkinson's disease "off" and "on" medication

5.1 Introduction

Impaired balance control and postural instability are among the main symptoms of Parkinson disease (Kandel et al., 2000). Postural instability has a major effect on the quality of life of individuals with PD since it increases the incidence of loss of balance and falls. Fall-induced injuries and fear of future falls limit patients' mobility (Bloem et al., 2001). Immobility has its own negative physiological and psychological consequences that further diminish the quality of life of individuals with PD.

It is well-known that postural instability of individuals with PD is exaggerated in specific circumstances. For example, individuals with PD show poorer balance and greater incidence of falls while performing specific tasks such as turning (Giladi et al., 1992; Bloem et al., 2001). Difficulty turning is a sensitive predictor of the two key symptoms of PD locomotion: freezing and falling (Stack et al., 2006). The association of turning with falls and freezing in individuals with PD emphasizes the importance of understanding the turning impairment in this patient population.

Previous research has shown that individuals with PD turn slower (Willems et al., 2007; Carpinella et al., 2007; Crenna et al., 2007; Visser et al., 2007; Mak et al., 2008), make wider turns (Willems et al., 2007) with narrower steps (Willems et al., 2007; Mak et al., 2008; Morris et al., 2001) and take more steps to complete the turn (Schenkman et al., 2000; Carpinella et al., 2007; Morris et al., 2001). Coordination of reorientation of body segments during turns embedded in locomotion is also impaired even in individuals with PD who demonstrate normal spatio-temporal gait parameters during straight walking and have negligible or no axial rigidity (Ferrarin et al., 2006; Crenna et al., 2007; Carpinella et al.,

2007). In comparison with age-matched healthy elderly, in PD participants initiation of reorientation of all body segments is significantly delayed. Furthermore, while healthy elderly turn their head, upper trunk and pelvis in succession, in individuals with PD the initiation of head reorientation is delayed. Individuals with PD turn their head and upper trunk together followed by rotation of pelvis (Ferrarin et al., 2006; Crenna et al., 2007; Carpinella et al., 2007).

The present study examines the effects of Parkinson's disease on coordination of reorientation of different body segments during turns embedded in locomotion. Huxham and colleagues have shown that the differences between individuals with PD and healthy controls in spatiotemporal footstep adjustments during turning are more marked for larger turns (Huxham et al., 2008). They also reported that in individuals with PD the disparity between the required and achieved magnitudes of turn is greater for larger turns, suggesting larger turns impose a greater challenge for individuals with PD (Huxham et al., 2008). We examined the possible effect of magnitude of the turn on the coordination of body segments during walking turns by incorporating two different degrees of turn in the protocol. The effect of dopaminergic medications on turning performance of individuals with PD was also examined by testing the PD participants "off" and "on" dopaminergic medications. The information obtained through this study contributes to understanding the etiology of turning impairment in individuals with PD and provides insights for therapeutic interventions to improve turning function and safety in this population.

5.2 Methods

5.2.1 Participants

Fourteen individuals with Parkinson's disease, 7 males and 7 females, 57 to 74 years old (mean±std age=67±4.8 years) participated in this study. The mean and standard deviation of the PD participants' height and body mass were 169±9cm and 75±9.9kg, respectively. Nineteen healthy community-dwelling older adults, 10 males and 9 females, 60 to 75 years old (mean±std age=66±4.2 years) volunteered to participate as the control group. The mean and standard deviation of the healthy older adults' height and body mass were 170±11cm and 77±17kg, respectively.

All individuals with Parkinson's disease were diagnosed with idiopathic PD by their neurologist. PD participants were either referred by their neurologist or were recruited from the local Parkinson's disease support groups. Participants were free from any significant orthopedic (e.g. fracture or severe osteoarthritis) or additional neurologic (e.g. stroke or traumatic brain injury) conditions. PD participants who were not able to walk continuously for a distance of 100m (one city block) without assistance (i.e., cane or walker), or were not able to follow simple commands were excluded from the study.

Healthy elderly were recruited through the University of Waterloo Research in Ageing Participant Pool (WRAP). Healthy older adults were free from any neurological, musculoskeletal or vestibular impairment, and had no history of falls in the six months prior to the experiment as verified by self-report.

All participants were informed about the experimental procedure before signing a consent form. All procedures were approved by the Office of Research Ethics at the University of Waterloo and the University of Western Ontario.

5.2.2 Procedure

For all participants information regarding participants' age, height, and medical history were collected. Participants' cognitive status was determined by the Modified Mini Mental Test (Teng and Chui, 1987). This test has a total possible score of 100 points; a score of less than 80 has been suggested as a criterion for cognitive impairment. Participants' trait anxiety level was examined by Beck Anxiety Inventory scale (Beck et al., 1988). This scale consists of 21 items, each describing a common symptom of anxiety with a total possible score of 0 to 63 points. A total score of less than 21, 22-35, and greater than 36 is considered as an indication of very low, moderate, and severe anxiety, respectively. No difference was found between the two groups in terms of anthropometric measures (age, height, and weight), Modified Mini Mental Test score, and BAI score. However, as expected the number of medications was significantly greater for PD participants than for healthy elderly ($t=-3.87$, $P=0.0005$). Mean and standard deviation of the number of medication was 4.4 ± 2.6 and 1.5 ± 1.6 for PD participants and healthy participants, respectively. This information is summarized in Table 5.1.

The participants' functional mobility was tested using the Timed-Up-and-Go (TUG) test and the 7m self-paced walking test. These tests have been shown to be both reliable and valid estimates of functional mobility (Podsiadlo and Richardson, 1991; Shumway-Cook et al.,

PD participants' ID	Gender	Age (year)	Height (cm)	Body Mass (kg)	3MS Score	BAI Score	TUG (s) ("off" Med)	TUG (s) ("on" Med)	Self-Paced (m/s) ("off" Med)	Self-Paced (m/s) ("on" Med)	# of Medications
1	F	64	165	64	96	1	10.4	9.4	0.66	0.88	3
2	F	57	170	77	95	15	11.8	12.6	0.88	0.97	3
3	M	70	168	68	97	2	9.3	9.2	1.07	1.08	3
4	F	64	152	73	96	8	11.7	9.2	0.83	1.3	8
5	M	67	178	84	89	2	10.6	11.1	0.91	1.02	9
6	M	70	185	91	100	1	9.7	9.6	0.83	0.89	2
7	F	68	160	83	95	0	10.5	9.8	1	1.05	5
8	M	62	165	80	99	4	10	7.7	1.05	1.24	3
9	F	70	163	62	97	25	8.1	9.8	1.10	1.1	2
10	M	73	175	77	97	13	9.9	10.3	1.07	0.96	5
11	M	62	185	63	98	20	13.2	11.5	1.11	1.09	4
12	M	63	173	91	98	4	11.6	11.5	0.96	0.98	1
13	F	70	165	71	97	23	9.9	11.6	0.82	1	9
14	F	74	165	66	93	17	9.2	9.4	1.16	1.2	4
Mean		67	169	75	96	9.6	10.4*	10.2*	0.96^{Ω}	1.05	4.4*
Std		4.8	9.3	9.9	2.7	8.9	1.3	1.3	0.14	0.13	2.6

Healthy Participants (n=19, 10 M, 9 F)	**Age (year)**	**Height (cm)**	**Body Mass (kg)**	**3MS Score**	**BAI Score**	**TUG (s)**	**Self-Paced (m/s)**	**# of Medications**
Mean	66	170	77	97	5	8.8	1.02	1.5
Std	4.2	11.4	17	3.6	3.4	1.0	0.15	1.6

Table 5.1. Characteristics of the PD participants (n=14) and healthy elderly (n=19). 3MS: Modified Mini-Mental State; BAI: Beck Anxiety Inventory; TUG: Timed-Up-and-Go score (s); Self-Paced: 7m self-paced walking speed (m/s). Stars indicate significant difference from comparable value for healthy participants (P<0.05, unpaired t-test). $^{\Omega}$ indicates significant difference between OFF and ON medication (P<0.05, paired t-test).

1997). The TUG was administered by observing and timing the participant rising from a chair, walking three meters, turning 180°, walking back to the chair and sitting down (Podsiadlo and Richardson, 1991). For each participant, three trials of the TUG were completed and the best score was recorded. The 7m self-paced walking test was also performed three times and the participant's best score was recorded (Table 5.1).

For PD participants, duration of Parkinson's disease (time since diagnosis) and the type and dose of their anti-parkinsonian medication was recorded. Clinical assessment of motor disability was performed using the motor component of the Unified Parkinson's Disease Rating Scale (UPDRS) (Fahn and Elton, 1987) when participants were "off" and "on" medication. This information is summarized in Table 5.2. Number of falls in the six months prior to testing was also recorded. Three participants with PD reported one fall during the six months prior to testing.

Participants were asked to change into tight-fitting clothing. Fourteen infra-red emitting diodes (IREDs) were mounted on fourteen anatomical landmarks of the participants' body to track the movements of their body. Twelve IREDs were mounted on the following anatomical landmarks bilaterally: ear, shoulder joint, anterior superior iliac spine, hip joint, lateral malleolus, and the big toe. One IRED was mounted on the chin and another IRED was placed on the participants' chest approximately 5cm below the jugular notch.

Each participant was tested for three straight walking trials and twelve trials of walking and turning. All trials were performed with the participants' arms crossed in front of their chest. This approach prevented the markers positioned on the pelvis area to be blocked by the

PD participant's ID	Duration of Disease[§]	Parkinsonian Medication	Daily Dose of Dopaminergic Medications (Levodopa Equivalents[Δ]) in milligram	UPDRS Score "Off" Med	UPDRS Score "On" Med
1	5	Pramipexole	201	30.5	16
2	4	Levodopa/Carbidopa, Trihexyphenidyl	400	38	32.5
3	9	Levodopa/Carbidopa	450	39	23.5
4	5	Levodopa/Carbidopa	500	22	12.5
5	6	Levodopa/Carbidopa	800	36	24
6	2	Rasagiline	1mg per day[Ω]	20.5	12
7	7	Ropinirole	200.04	13.5	6.5
8	5	Levodopa/Carbidopa & Pramipexole	401.5	14.5	6
9	8	Levodopa/Carbidopa	450	12	12
10	1	Rasagiline	1mg per day[Ω]	18	9.5
11	8	Levodopa/Carbidopa	1000	29	20.5
12	3	Levodopa/Carbidopa	400	19.5	12
13	5	Levodopa/Carbidopa & Ropinirole	733.36	14	8
14	4	Levodopa/Carbidopa	600	25	22
Mean	5			24*	16
Std	2.3			9.4	7.8

Table 5.2. Parkinson patients (n=14). [§]Duration of Disease: years since diagnosis; UPDRS: Unified Parkinson's Disease Rating Scale; * indicates significant difference between PD "off" and "on" medication (P<0.05, paired t-test). [Δ] Calculated based on the formula by Hobson et al., 2002. [Ω] Rasagiline is a new medication, and currently there is no formula for calculating the levodopa equivalent of this medication.

swinging arms. Furthermore, arm swinging during walking is reduced in individuals with Parkinson's disease (Martin, 1967). By asking the participants to walk with their arms crossed in front of their chest we eliminated the possible contribution of the arm swing on the segment reorientation from both groups. Experimental setup is shown in Figure 5.1. In the straight walking trials participants were asked to walk straight ahead on a 7m path. During walking and turning trials participants were asked to walk straight ahead for about 4 meters to reach the "turning zone" and then turn off at an angle of 45° or 90° to either their right or left and continue to walk for an additional 3 meters. A circle (diameter = 50cm) was drawn on the lab floor to indicate the "turning zone." A pylon was placed at the end of each of the potential travel paths to provide a continuous visual cue about the direction of the turn. Before each trial participants were advised about the direction and the magnitude of the turn for that trial, i.e., they were told towards which pylon they should walk. Participants were instructed to walk straight forward until they reach the turning zone at which they were asked to turn into the designated path (without stopping at the turning zone) and to keep walking until they reach the pylon positioned at the end of that path. Participants were instructed not to adjust their step length to step on the turning zone. They were told that the circle was there to just guide them as to where about they should make their turn.

Upon completion of all the trials, participants' spinal flexibility was measured using the Functional Axial Rotation (FAR) test (Schenkman et al., 2001). Participants were asked to sit on a stool with their feet flat on the floor and their arms resting on their lap. Participants were instructed to turn their head and trunk to their right and then left as far as they could to look at the wall behind them without lifting their feet from the floor or rising from the stool.

Movements of the head and trunk were recorded using the Optotrak cameras. Angular displacements of the head and shoulders in the yaw plane were calculated using the Optotrak data. These measures indicate the flexibility of the cervico-thoraco-lumbar and thoraco-lumbar spine. This information is summarized in Table 5.3.

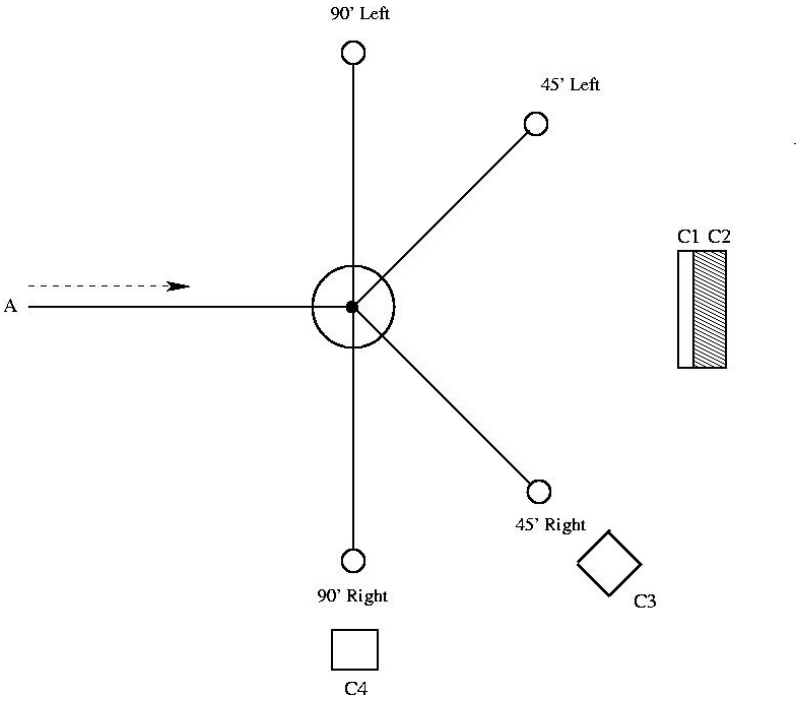


Figure 5.1. Figure shows the top view of the experimental setup. Trials started with participants standing at point A. On the straight walking trials participants walked straight ahead for about 7m and stopped in front of the two horizontal cameras (C1 and C2). During the turning trials participants walked straight forward until they reached the turning zone (the large circle) at which they turned into the designated path and kept walking until they reached the pylon positioned at the end of that path. Small circles represent the pylons. C1 and C2 represent the two horizontal Optotrak cameras which were positioned on top of one another. C3 and C4 represent the two vertical cameras.

PD participants (n=14)	FAR Head ("off" Med)	FAR Shoulder ("off" Med)	FAR Head ("on" Med)	FAR Shoulder ("on" Med)
Mean	93.8	36.4	91	35.6
Std	14.9	9.7	16	11.6
Healthy Participants(n=19)	**FAR Head**	**FAR Shoulder**		
Mean	99.5	42.8		
Std	13.4	10.2		

Table 5.3. Functional Axial Rotation score (FAR) for PD participants "off" and "on" medication and healthy participants. Scores shown are the average of the scores for the right and left sides.

PD participants were tested both "off" and "on" dopaminergic medication. They were asked to skip the last dose of their anti-parkinsonian medication prior to coming to the laboratory. Upon arrival, they were tested while they were "off" dopaminergic medications. After completion of the "off medication" testing, PD participants were asked to take their dopaminergic medication. The second round of the experiment started when the participant reported that he/she is in his/her "on medication" state (about an hour after taking the medication). For PD participants the Functional Axial Rotation (FAR) test was performed in both "off" and "on" medication status (Table 5.3).

For both groups the three straight walking trials were performed at the beginning and were followed by the walking and turning trials. The order of the right-turn and left-turn trials was completely randomized. Each participant performed three trials in each of the

aforementioned conditions. Therefore, in total healthy participants performed 15 trials and PD participants performed 30 trials (15 trials in each of the "off" and "on" medication conditions). However, for both groups data were collected only during the straight ahead and right-turn trials (a total of 9 trials for healthy and 18 for PD participants). Participants were unaware that data were not being collected during the left-turn trials.

Rest periods were provided throughout the experiment upon participants' request. During the trials an assistant followed the participant closely to assist in the event of a fall. Throughout the experimental trials, movements of the participants' body were videotaped.

5.2.3 Data collection

Two horizontal and two vertical Optotrak 3D imaging system cameras (Northern Digital Inc., Canada) were used to collect kinematic data. The horizontal cameras were positioned on top of one another and were placed in front of the participant and at the end of the straight walking path. If only one camera was used, during the straight walking trials as the participant passed the turning zone and approached the camera the toe markers would fall outside of the camera's view. Therefore, two cameras were used at the end of the straight walking path. The bottom horizontal camera was tilted downward to allow capturing of the toe markers during the last part of the straight walking trials. This set up allowed collecting sufficient data during the straight walking trials. The vertical cameras were positioned at the participant's right side. This arrangement allowed collection of the data from two steps prior to two steps after the turning step. Optotrak data were recorded at 120 Hz.

5.2.4 Data processing

The Optotrak data were low-pass filtered (Butterworth) prior to analyses with a cut-off frequency of 6 Hz. For each trial and for each participant, walking velocity was calculated using the data obtained from the two markers placed on the big toes. The distance traveled by the toe markers from the time that these markers came into the cameras' view to the time that they fell out of the cameras' view (equivalent to at least four steps for both straight walking and turning trials) was calculated. Walking velocity was computed by dividing the distance traveled by the time it took to travel that distance. Excluding the initial and final portions of the trial (i.e., before the toe markers came to the cameras' view and after they fell out of the cameras' view) eliminated the confounding effects of acceleration and deceleration on calculations of the walking velocity.

The yaw angular displacement profiles of the head, shoulder (upper trunk), and pelvis in the global reference frame were determined from the three non-co-linear markers placed on each of the aforementioned segments. The three markers define the rigid body of each segment, making it possible to determine its orientation with respect to gravito-inertial frame. For each participant, the mean and standard deviation values of the head, shoulder, and pelvis yaw during the three straight walking trials were calculated. The initiation of reorientation of head, shoulder, and pelvis in yaw plane during a turning trial was calculated as the point in time that the angular displacement data indicated the segment had turned towards the new direction providing the deviation continued beyond the average range of angular displacement of the segment during the straight walking trials.

Toe displacement profiles were used to determine the onset of change in the mediolateral foot displacement towards the new direction of the travel path for the right and left feet. For each participant the data obtained from the three straight walking trials were averaged. Standard deviation (std) profiles over time were generated. For turning trials, the onset of foot mediolateral deviation into the designated travel direction was calculated as the point in time that test data deviated from the straight walking trials average profile providing the deviation continued beyond the control 2std boundary. The onset times of the mediolateral displacements of the feet towards the new direction of the travel path were examined to determine whether the first step was taken with the right or the left foot (i.e., the turn was a step or a spin turn).

The time at which head reorientation towards the new direction of travel path initiated was considered the reference time (time = 0 ms). DT-Shoulder, DT-Pelvis and DT-First Step refer to the delay time (DT) for reorientation of shoulder, pelvis, and the foot that took the first step, regardless the preparatory or main step (for definition of the preparatory and main step see below), towards the new direction of the travel path (respectively) relative to the aforementioned reference time.

For each trial the peak angular velocity of head, shoulder and pelvis in the yaw direction after the onset of the segment's movement was calculated. The time at which the head reached its peak angular velocity was considered the reference time (time = 0 ms). The latencies of the peak angular velocity of shoulder and pelvis relative to this reference time were computed.

Examining the data revealed that in many trials the reorientation of each foot towards the new travel direction was completed over two steps rather than one; a *preparatory step* with small mediolateral deviation of the foot towards the new direction of the travel path and a *main step* with significant deviation of the foot towards the new direction of the travel path. To examine the prevalence of the preparatory steps, for each foot the magnitude of mediolateral displacement towards the new direction of the travel path was calculated for the first two steps following the onset of reorientation of that foot towards the new direction (step 1 and step 2). If the magnitude of mediolateral displacement towards the new direction of the travel path during step 1 was less than one third of the comparable value for step 2, step 1 was considered a preparatory step. Turns performed with a main step are called *single-step turns*, and turns performed with a preparatory and a main step are called *double-step turns*.

5.2.5 Data Analysis

The percentages of trials with double-step and single-step turns were calculated to provide an estimate of the prevalence of preparatory steps in turning performance of healthy elderly and PD participants "off" and "on" medication. For each group and for each condition, a binomial proportion test was used to test for the significance of the differences in the prevalence of the double-step and single-step turns. For each condition the difference in the percentages of the double-step and single-step turns between groups was examined by a t-test for the equality of proportions.

To determine if healthy older adults and PD participants "off" and "on" medication had a preference for step turn vs. spin turn, the percentages of the step turns (in which the *main step* initiating the reorientation towards the new direction was taken with the right foot) and the spin turns (in which the *main step* initiating the reorientation towards the new direction was taken with the left foot) were computed. For each group and for each condition, a binomial proportion test was used to test for the significance of the differences in the prevalence of the step and spin turns. For each condition the difference in the percentages of the step and spin turns between groups was examined by a t-test for the equality of proportions.

For healthy controls and PD participants "off" and "on" medication, the effect of turn type (step vs. spin) on the timing and sequence of reorientation of different body segments towards the new direction of travel was examined by comparing DT-Shoulder, DT-Pelvis, and DT-First Step obtained from the trials performed with the two different types of turn. Results showed no significant difference between the step and spin turns in the timing and sequence of reorientation of different body segments towards the new direction of travel during the 45° and 90° turns for healthy elderly and PD participants "off" medication. For PD participants "on" medication however, turn type had significant effect on the DT-First Step during both 45° and 90° turns. During the 45° turns, average DT-First Step was significantly shorter when two of the three trials were performed with step turns than when the three trials were performed with spin turns (mean DT-First Step=427 and 930ms, respectively). During the 90° turns, average DT-First Step was significantly shorter when

two of the three trials were performed with step turns than when all three trials were performed with either step or spin turns (mean DT-First Step=755, 1163, and 1385ms, respectively).

However, it should be noted that during both 45° and 90° turns, even the shortest DT-First Step value (which in both conditions was observed when two of the three trials were performed with step turns) was significantly longer than average DT-shoulder and DT-pelvis. This means that although for PD participants "on" medication turn type had a significant effect on the DT-First Step during both 45° and 90° turns, this effect did not modify the sequence of reorientation of different body segments. Therefore, data obtained from all trials (regardless of the type of the turn) was pooled together and used in the subsequent analyses.

5.2.5.1 Effects of Parkinson's disease on the coordination of head and body reorientation during turns embedded in locomotion

Data collected from the healthy elderly and PD participants while "off" medication was used to examine the effects of Parkinson's disease on the coordination of head and body reorientation during turns embedded in locomotion. In the original analyses, gender was included as a factor. However, results revealed no significant main or interaction effect of gender on the timing and sequence of body segment reorientation and angular velocity values. Therefore, considering the small number of participants in each gender group the gender factor was removed to preserve the power of the analyses.

To examine the effect of Parkinson's disease and magnitude of the turn on the sequence and timing of reorientation of different body segments during turns embedded in locomotion, a

three way repeated measure ANOVA with group (healthy vs. PD) as between factor and body segment (shoulder, pelvis, foot), and magnitude of the turn (45°, 90°) as within factors was performed on the delay times (DTs) in the initiation of reorientation of different body segments relative to the initiation of reorientation of the head. Since the initiation of reorientation of head is considered as the reference time (time = 0), head could not be included as a segment in the above analysis. Therefore, one-way t-tests were performed to determine if the means of the delay times in the initiation of reorientation of shoulder, pelvis and foot are significantly different from zero (initiation of head reorientation). A Bonferroni correction was used to correct for multiple comparisons.

To compare the peak angular velocity of different body segments during turning between healthy elderly and PD participants and to examine the effect of magnitude of the turn on the peak angular velocities, a three way repeated measure ANOVA with group (healthy vs. PD) as between factor and body segment (head, shoulder, pelvis), and magnitude of the turn (45°, 90°) as within factors was performed on the peak angular velocities of the head, shoulder and pelvis.

To examine the effect of Parkinson's disease and magnitude of the turn on the sequence and timing of the peak angular velocity of different body segments during turns embedded in locomotion, a three way repeated measure ANOVA with group (healthy vs. PD) as between factor and body segment (shoulder, pelvis), and magnitude of the turn (45°, 90°) as within factors was performed on the latencies of the peak angular velocity of shoulder and pelvis relative to the peak angular velocity of the head.

To examine the effect of Parkinson's disease on the amount of turn achieved by different body segments at the onset of mediolateral foot displacement during small and large turns, a three way repeated measure ANOVA with group (healthy vs. PD) as between factor and body segment (head, shoulder, pelvis), and magnitude of the turn (45°, 90°) as within factors was performed on the amount of turn achieved by the onset of mediolateral foot displacement.

5.2.5.2 Effects of dopaminergic medications on the coordination of head and body reorientation during turns embedded in locomotion in individuals with Parkinson's disease

Data obtained from PD participants while "off" and "on" medication was analyzed to examine any possible effect of dopaminergic medications on the coordination of head and body reorientation during turns embedded in locomotion in individuals with PD. In the original analyses gender was included as a factor. However, since the results revealed no significant main or interaction effect of gender on any of the variables of interest the gender factor was removed from the analyses.

To examine the effect of dopaminergic medication on the sequence and timing of reorientation of different body segments during different magnitudes of turns embedded in locomotion, a three way repeated measure ANOVA with medication condition ("off" and "on"), body segment (shoulder, pelvis, foot), and magnitude of the turn (45°, 90°) as within factors was performed on the delay times in the initiation of reorientation of different body segments relative to the initiation of reorientation of the head. Since the initiation of

reorientation of head is considered as the reference time (time = 0), head could not be included as a segment in the above analysis. Therefore, one-way t-tests were performed to determine if the means of the delay times in the initiation of reorientation of shoulder, pelvis and foot are significantly different from zero (initiation of head reorientation). A Bonferroni correction was used to correct for multiple comparisons.

To examine the effect of dopaminergic medication and magnitude of the turn on the peak angular velocity of different body segments, a three way repeated measure ANOVA with medication condition ("off" and "on"), body segment (head, shoulder, pelvis), and magnitude of the turn (45°, 90°) as within factors was performed on the peak angular velocities of different body segments.

To examine the effect of dopaminergic medications and magnitude of the turn on the sequence and timing of the peak angular velocity of different body segments, a three way repeated measure ANOVA with medication condition ("off" and "on"), body segment (shoulder, pelvis), and magnitude of the turn (45°, 90°) as within factors was performed on the latencies of the peak angular velocity of shoulder and pelvis relative to the peak angular velocity of the head.

To examine the effect of dopaminergic medications and magnitude of the turn on the amount of turn achieved by the onset of mediolateral foot displacement, a three way repeated measure ANOVA with medication condition ("off" and "on"), body segment (head, shoulder,

pelvis), and magnitude of the turn (45°, 90°) as within factors was performed on the amount of turn achieved by the onset of mediolateral foot displacement.

In conditions that a main or interaction effect of a factor was revealed, Tukey's Studentized Range (HSD) Test was performed to determine which means were significantly different from the others. For all tests, a significance value (P) of less than 0.05 was used to test statistical significance.

5.3 Results

Figure 5.2. shows the percentage of trials with double-step and single-step turns for healthy elderly and PD participants "off" and "on" medication during the 45° and 90° turns. Binomial proportion test revealed significant differences in prevalence of the double-step and single-step turns during the 45° turns for healthy elderly ($Z=-2.8316$, $P=0.0065$), with single-step turns being more common than double-step turns (69.1% vs. 30.9%, respectively). Furthermore, Binomial proportion test revealed significant differences in prevalence of the double-step and single-step turns during the 90° turns for PD participants "off" ($Z=2.3426$, $P=0.0275$), and "on" ($Z=2.2136$, $P=0.0385$) medication. For PD participants, in both medication conditions, double-step turns were more common during the 90° turns.

T-tests for the equality of proportions revealed no significant differences in the prevalence of double-step and single-step turns in each magnitude of the turn between healthy elderly and PD participants "off" and "on" medication. Furthermore, in each magnitude of the turn the

percentage of double-step and single-step turns was not different between PD participants "off" and "on" medication.

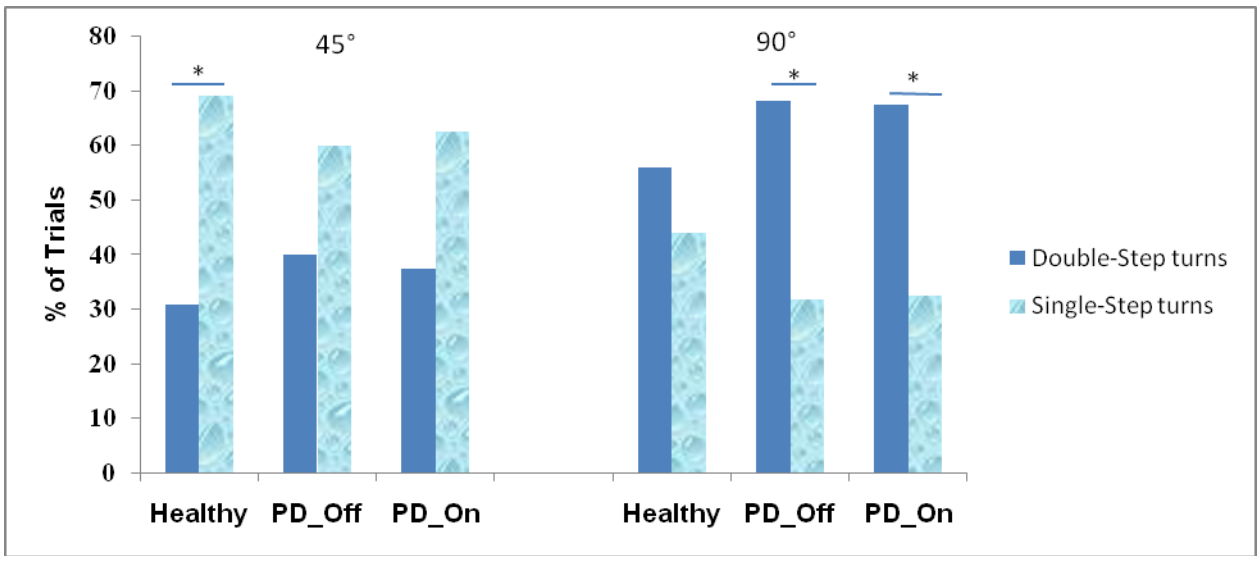


Figure 5.2. The percentage of trials performed with double-step and single-step turns for healthy elderly and PD participants "off" and "on" medication during the 45° and 90° turns. Stars indicate significant difference (α=0.05)

Figure 5.3. shows the percentage of the step turns and the spin turns for healthy elderly and PD participants "off" and "on" medication during the 45° and 90° turns. Binomial proportion test revealed significant difference between the percentage of step and spin turns only for PD participants "off" medication and only during the 90° turns. During the 90° turns for PD participants "off" medication the percentage of the step turns was significantly higher than the percentage of the spin turns (Z=-2.9673, P=0.0043). T-tests for the equality of proportions revealed no significant differences in the prevalence of step and spin turns in each magnitude of the turn between healthy elderly and PD participants "off" and "on"

medication. Furthermore, in each magnitude of the turn the percentage of step and spin turns was not different between PD participants "off" and "on" medication.

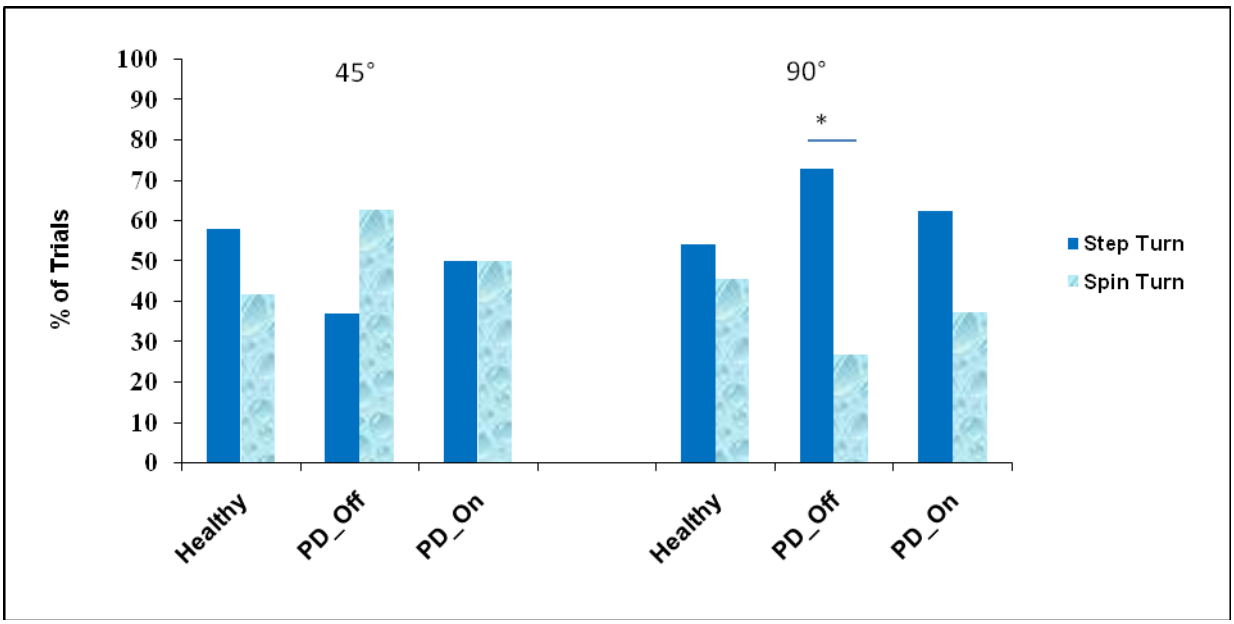


Figure 5.3. The percentages of step and spin turns for healthy elderly and PD participants "off" and "on" medication during the 45° and 90° turns. Star indicates significant difference (α=0.05)

5.3.1 Effects of Parkinson's disease on the coordination of head and body reorientation during turns embedded in locomotion

5.3.1.1 Sequence and timing

ANOVA revealed significant effects of segment ($F(2,62)=216.96$, $P<0.0001$), and segment*group ($F(2,62)=9.66$, $P=0.0002$) on the sequence and timing of reorientation of different body segments. Further examination revealed that healthy elderly turned their shoulder and pelvis in unison. The simultaneous reorientation of the shoulder and pelvis in

the yaw plane was followed by reorientation of the feet (mean±std=164±224, 248±216, and 721±250ms for shoulder, pelvis, and foot, respectively) (Figure 5.4). For PD participants however, there was a significant delay between the initiation of reorientation of shoulder and pelvis. Mean and standard deviation of the delay time in the initiation of reorientation of shoulder, pelvis, and foot in PD participants was 91±158, 357±352, and 960±213ms, respectively (Figure 5.4). Furthermore, results of the one-way t-tests revealed that averaged across the two magnitudes of the turn, for both groups of participants, DT-shoulder, DT-pelvis and DT-first step were significantly different from zero ($t=4.51$, $P<0.0001$ for DT-shoulder; $t=7.06$, $P<0.0001$ for DT-pelvis; $t=17.78$, $P<0.0001$ for DT-first step for healthy elderly; and $t=3.03$, $P=0.0053$ for DT-shoulder; $t=5.36$, $P<0.0001$ for DT-pelvis; $t=23.85$, $P<0.0001$ for DT-first step for PD participants). These results indicate that healthy individuals initiated turning with rotation of the head, followed by simultaneous rotation of the shoulder and pelvis and lastly the mediolateral displacement of the leading foot. In PD participants however, reorientation of body segments followed a top-down sequence with significant delay among onset of reorientation of all body segments. The different behavior of PD participants was due to the fact that while the delay time in the initiation of reorientation of shoulder was not different between the two groups (mean±std=164±224 vs. 91±158ms for healthy elderly and individuals with PD, respectively), the delay time in the initiation of reorientation of pelvis was significantly longer for PD participants (mean±std=357±352ms) than healthy elderly (mean±std=248±216ms) (Figure 5.4).

Delay time in initiation of mediolateral foot displacement was significantly longer for PD participants than healthy elderly (mean±std=960±213 vs. 721±250ms for PD participants and healthy elderly, respectively).

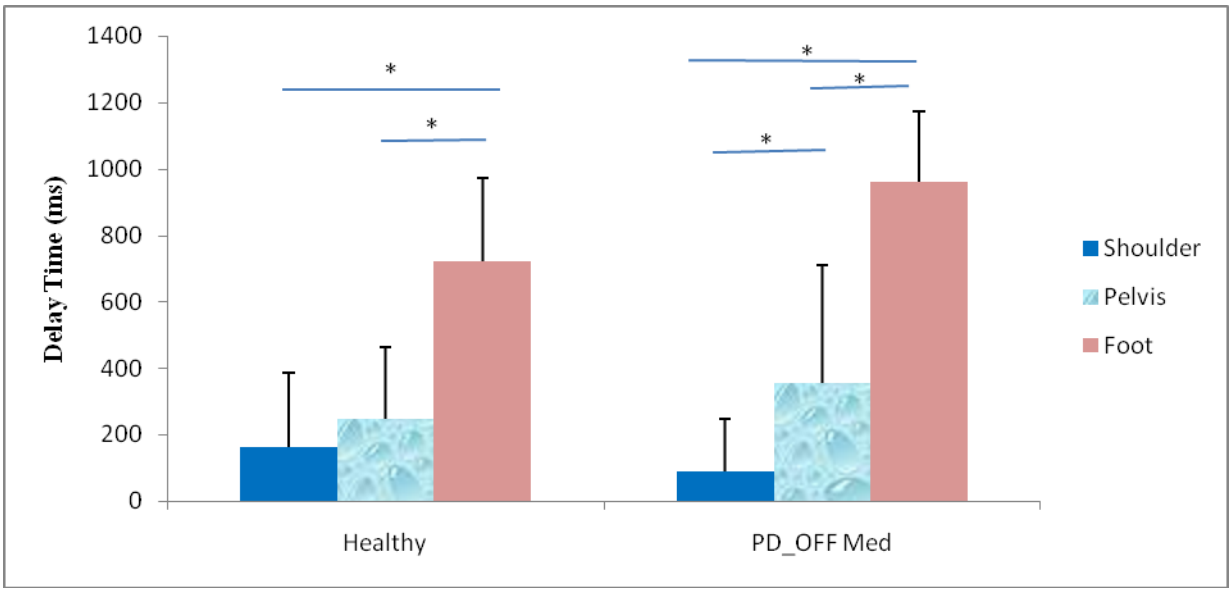


Figure 5.4. Mean and standard deviation (error bars) of the delay times (DTs) in the initiation of reorientation of shoulder, pelvis and foot relative to the initiation of head reorientation for healthy elderly and PD participants while "off" medication. Stars indicate significant differences (α=0.05).

5.3.1.2 Velocity

The three way ANOVA revealed significant main effect of group ($F(1,31)=47.17$, $P<0.0001$), segment ($F(2,62)=4.55$, $P=0.0143$), and magnitude of the turn ($F(1,31)=475.95$, $P<0.0001$) on the peak angular velocities of different body segments during turning. Segment*group

(F(2,62)=4.00, P=0.0232), magnitude*group (F(1,31)=31.14, P<0.0001), and segment*magnitude (F(2,62)=12.73, P<0.0001) interaction effects were also significant.

Examining the segment*group interaction effect revealed that regardless of the magnitude of the turn, the peak angular velocity for all body segments was significantly smaller for PD participants than healthy elderly (Figure 5.5). Mean and standard deviation of the peak angular velocity of head, shoulder, and pelvis were 62.2±25, 62.3±19.5, and 69.7±17.5deg/s for PD participants, and 97.1±39.3, 88.7±32.4, and 93.4±35deg/s for healthy elderly, respectively. Furthermore, for healthy participants the peak angular velocity of head was greater than the peak angular velocity of shoulder and pelvis, even though this difference was significant only between head and shoulder. For PD participants however, the peak angular velocity of pelvis was significantly greater than the peak angular velocity of head and shoulder. For PD participants the peak angular velocity of head and shoulder were not different from each other (Figure 5.5).

Examining the magnitude of the turn*group interaction effect revealed that for both groups the peak angular velocity (averaged across head, shoulder, and pelvis) was significantly smaller during the 45° than the 90° turns (Figure 5.6). Furthermore, at each magnitude of the turn the peak angular velocity was significantly greater for healthy participants than for PD participants (Figure 5.6). Averaged across different body segments the mean and standard deviation of the peak angular velocity for healthy elderly and PD participants were 63±12.1 and 47±10.2deg/s during the 45° turns, and 123.1±23.7 and 82.5±11.8deg/s during the 90° turns, respectively (Figure 5.6).

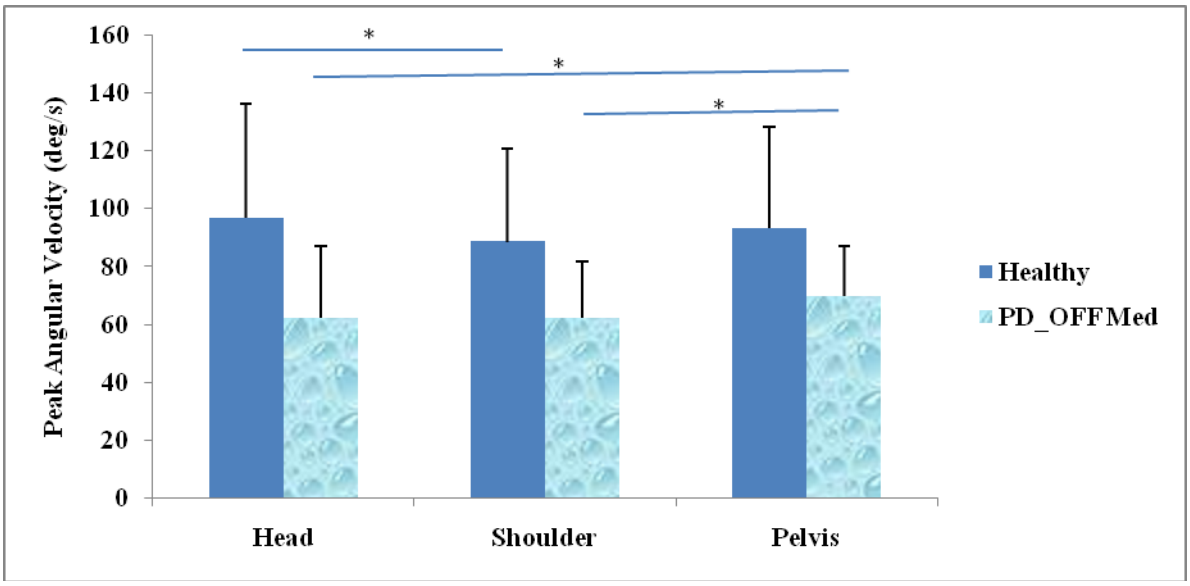


Figure 5.5. Mean and standard deviation (error bars) of the peak angular velocity of head, shoulder, and pelvis in yaw plane during turns embedded in locomotion for healthy elderly and PD participants "off" medication averaged across the two different magnitudes of the turn. Stars indicate significant differences (α=0.05).

Examining the segment*magnitude interaction revealed that for all body segments the peak angular velocity was significantly smaller during the 45° turns than during the 90° turns (Figure 5.7). Mean and standard deviation of the peak angular velocity of head, shoulder, and pelvis were 53.29±15.17, 55.34±14.62, and 59.93±10.85deg/s during the 45° turns, and 111.30±31.03, 99.64±25.7, and 106.8±26.58deg/s during the 90° turns, respectively (Figure 5.7). Furthermore, during the 45° turns the peak angular velocity of pelvis was significantly greater than the peak velocity of head and shoulder. Peak angular velocity of head and shoulder were not different from each other. During the 90° turns however, the peak angular velocity of head and pelvis were significantly greater than the peak angular velocity of shoulder (Figure 5.7).

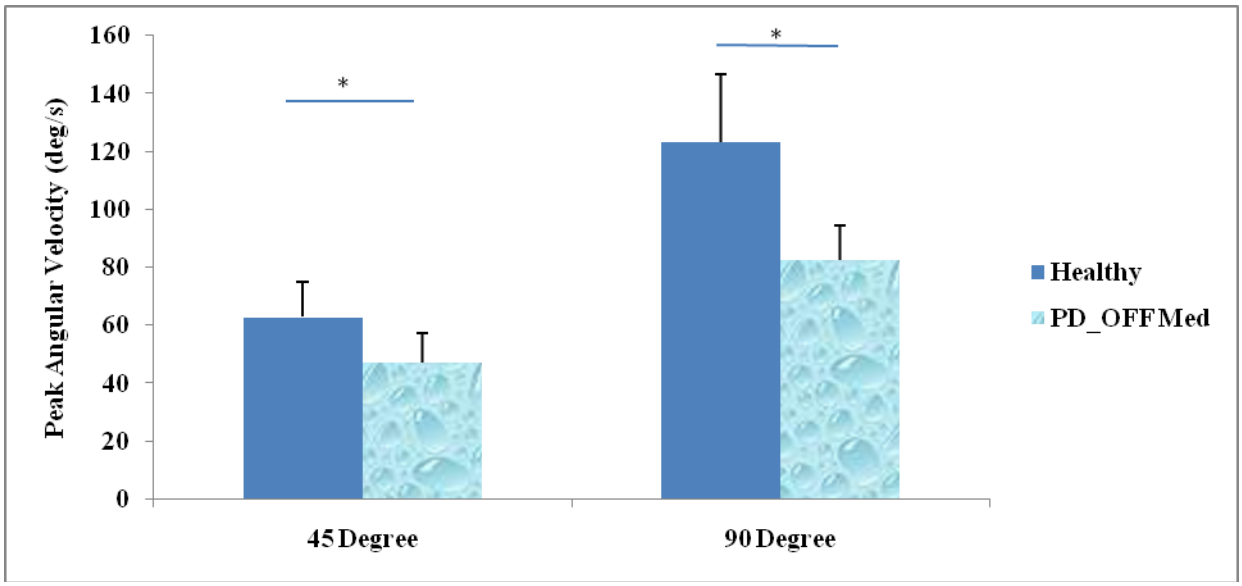


Figure 5.6. Mean and standard deviation (error bars) of the peak angular velocity (averaged across head, shoulder, and pelvis) in yaw plane during turns embedded in locomotion for healthy elderly and PD participants "off" medication at the two different magnitudes of the turn. Stars indicate significant differences (α=0.05).

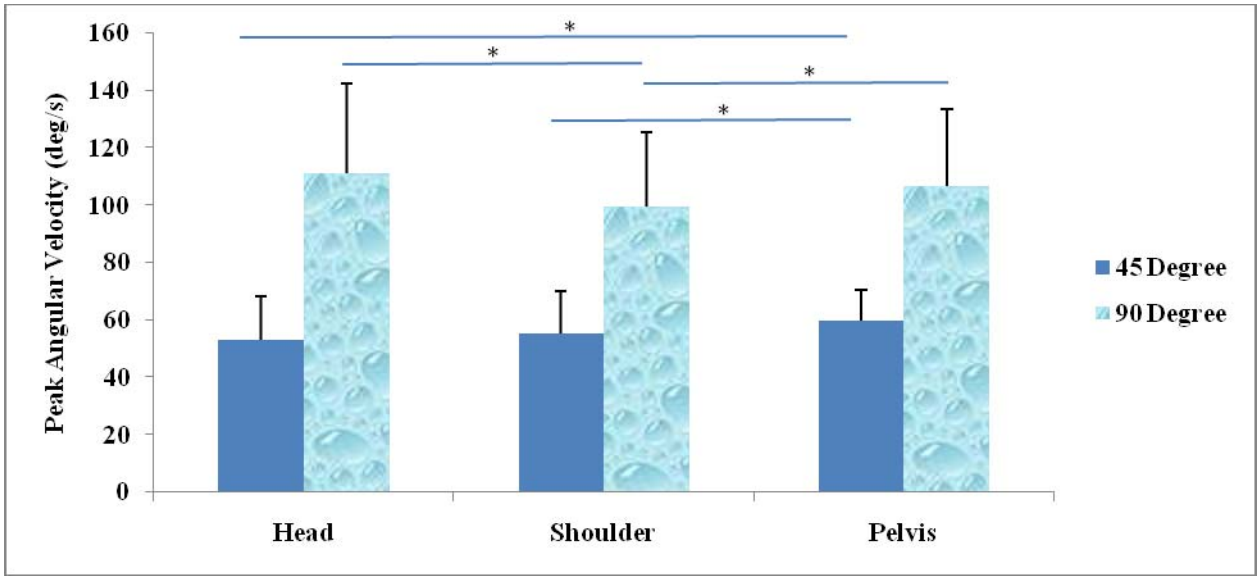


Figure 5.7. Mean and standard deviation (error bars) of the peak angular velocity of head, shoulder, and pelvis in yaw plane during 45° and 90° turns embedded in locomotion averaged across the two groups of participants. Stars indicate significant differences (α=0.05).

The three way ANOVA revealed significant interaction effect of segment*magnitude of the turn ($F(1,31)=7.89$, $P=0.0085$) on the latencies of the peak angular velocity of shoulder and pelvis relative to the peak angular velocity of the head. Tukey's analyses revealed that the latency of the peak angular velocity of shoulder was significantly longer during the 45° turns than the 90° turns (mean±std=211±224 and 114±150ms, respectively). However, the latency of the peak angular velocity of pelvis remained unchanged during the 45° and 90° turns (mean±std=155±237 and 153±216ms, respectively) (Figure 5.8).

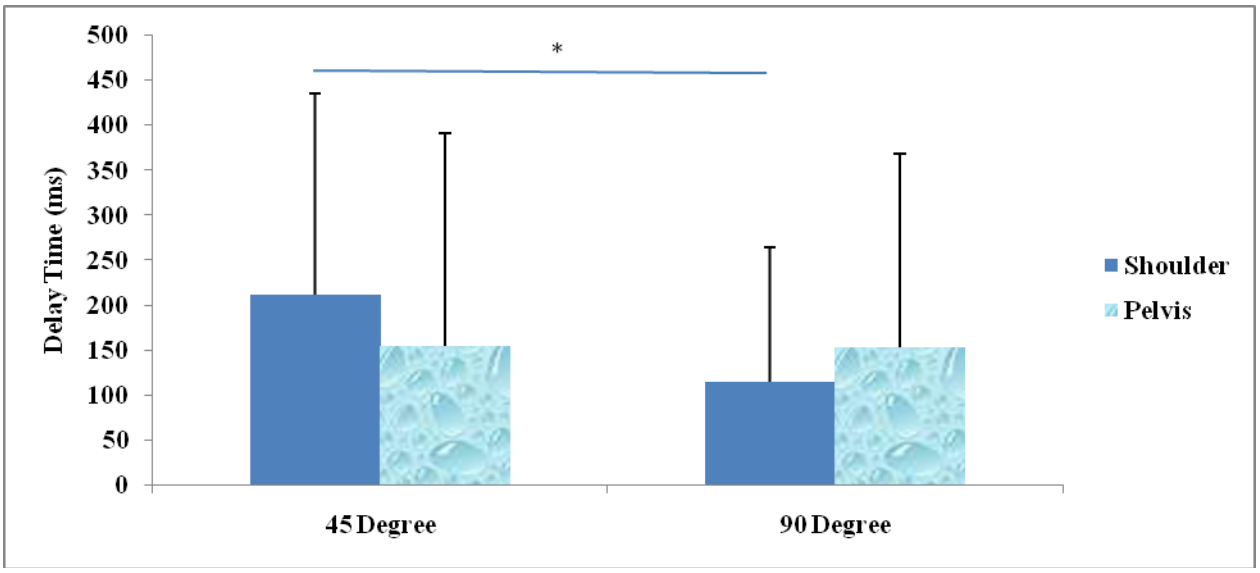


Figure 5.8. Mean and standard deviation (error bars) of the latencies of the peak angular velocity of shoulder and pelvis relative to the peak angular velocity of the head during turns embedded in locomotion at two different magnitudes of turn and averaged across the two groups of participants. Star indicates significant difference (α=0.05).

5.3.1.3 Magnitude

The three way ANOVA revealed significant effect of segment ($F(2,62)=38.69$, $P<0.0001$), magnitude of the turn ($F(1,31)=52.20$, $P<0.0001$), and segment*magnitude of the turn ($F(2,62)=28.13$, $P<0.0001$) on the amount of turn achieved by the onset of mediolateral foot displacement. Tukey's analyses revealed that for all body segments the amount of turn was significantly greater during the 90° turns than during 45° turns (Figure 5.9). The mean and standard deviation of turn were 33.8±12.5 and 17.9±6.8deg for head, 27.7±10.1 and 14.8±5.8deg for shoulder, and 23±8.7 and 13.9±6.3deg for pelvis during the 90° and 45° turns, respectively.

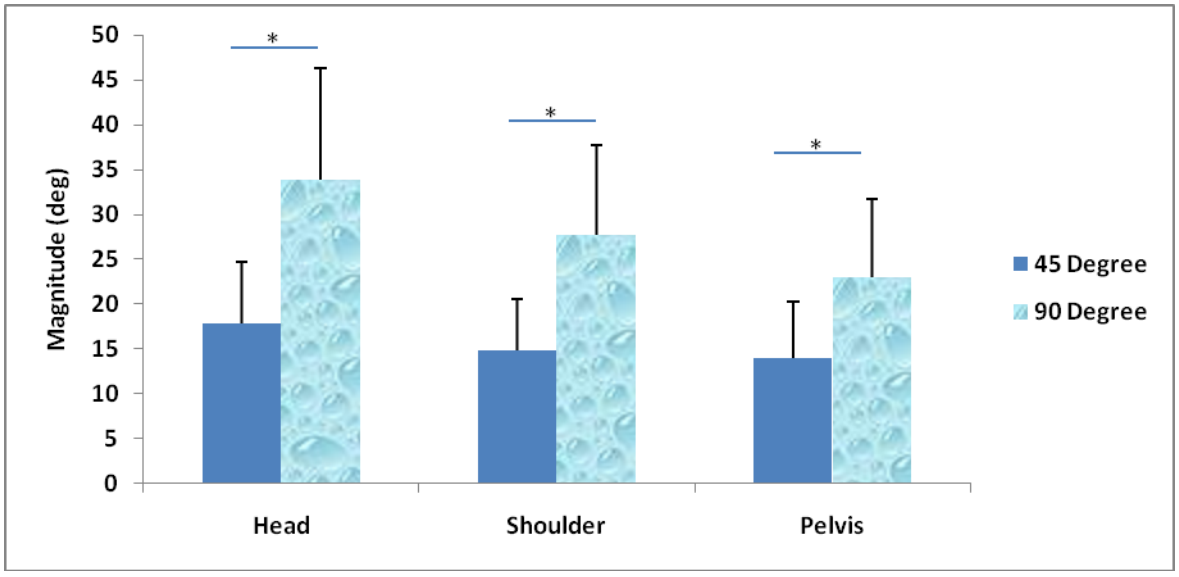


Figure 5.9. Mean and standard deviation (error bars) of the magnitude of head, shoulder, and pelvis turn at the onset of mediolateral displacement of the leading foot during the 45° and 90° turns averaged across the two groups of participants. Stars indicate significant differences ($\alpha=0.05$).

During the 90° turns the amount of turn achieved by the onset of mediolateral foot displacement was significantly different among different body segments. During the 45° turns however, the amounts of shoulder and pelvis turn were not different from each other. Group had no main or interaction effect on the degree of turn achieved by any segment by the onset of mediolateral displacement of the leading foot. Averaged across the 45° and 90° turns, the mean and standard deviation of the amount of turn achieved by the onset of mediolateral displacement of the leading foot was 27.5±14.2 and 23.7±10.4deg for head, and 21.9±11.5 and 20.4±8.8deg for shoulder, and 19.4±9.1 and 17.3±8.6deg for pelvis, for healthy elderly and PD participants, respectively.

5.3.2 Effects of dopaminergic medications on the coordination of head and body reorientation during turns embedded in locomotion in individuals with Parkinson's disease

5.3.2.1 Sequence and timing

The three way ANOVA on data obtained from PD participants "off" and "on" medication revealed only significant main effect of segment ($F(2,26)=126.53$, $P<0.0001$) on the sequence and timing of reorientation of different body segments during turns embedded in locomotion. Tukey's analyses revealed significant differences among delay times in the initiation of reorientation of shoulder, pelvis, and foot. Mean and standard deviation of DT-shoulder, DT-pelvis, and DT-first step were 100±156, 356±301, and 949±233ms, respectively. Medication condition had no significant main or interaction effect on the sequence and timing of reorientation of different body segments. Results of the one-way t-tests revealed that averaged across the two magnitudes of the turn, in both "off" and "on"

conditions, DT-shoulder, DT-pelvis and DT-first step were significantly different from zero ($t=3.03$, $P=0.0053$ for DT-shoulder; $t=5.36$, $P<0.0001$ for DT-pelvis; $t=23.85$, $P<0.0001$ for DT-first step for PD participants "off" medication; and $t=3.70$, $P=0.0010$ for DT-shoulder; $t=7.65$, $P<0.0001$ for DT-pelvis; $t=19.44$, $P<0.0001$ for DT-first step for PD participants "on" medication). These results indicate that in PD participants, regardless of the medication condition, reorientation of body segments followed a top-down sequence with significant delay among onset of reorientation of all body segments.

5.3.2.2 Velocity

ANOVA revealed significant main effects of segment ($F(2,26)=8.33$, $P=0.0016$) and magnitude of the turn ($F(1,13)=306.07$, $P<0.0001$) on the peak angular velocity of different body segments. Segment*magnitude interaction effect was also significant ($F(2,26)=12.94$, $P=0.0001$). Examining the segment*magnitude interaction effect revealed that for all body segments the peak angular velocity was significantly smaller during the 45° than the 90° turns (Figure 5.10). Mean and standard deviation of the peak angular velocity of head, shoulder, and pelvis were 41.3±7.2, 46.4±11, and 55.5±9.6deg/s during the 45° turns, and 86.5±16.1, 81.5±16, and 88.9±14.2deg/s during the 90° turns, respectively (Figure 5.10). During the 45° turns, the peak angular velocity of head, shoulder, and pelvis were significantly different from each other, being smallest for head and largest for pelvis. During the 90° turns however, the peak angular velocity of head and pelvis were significantly greater than the peak angular velocity of shoulder. The peak angular velocity of head and pelvis were

not different from each other (Figure 5.10). Medication condition had no significant main or interaction effect on the peak angular velocities of different body segments.

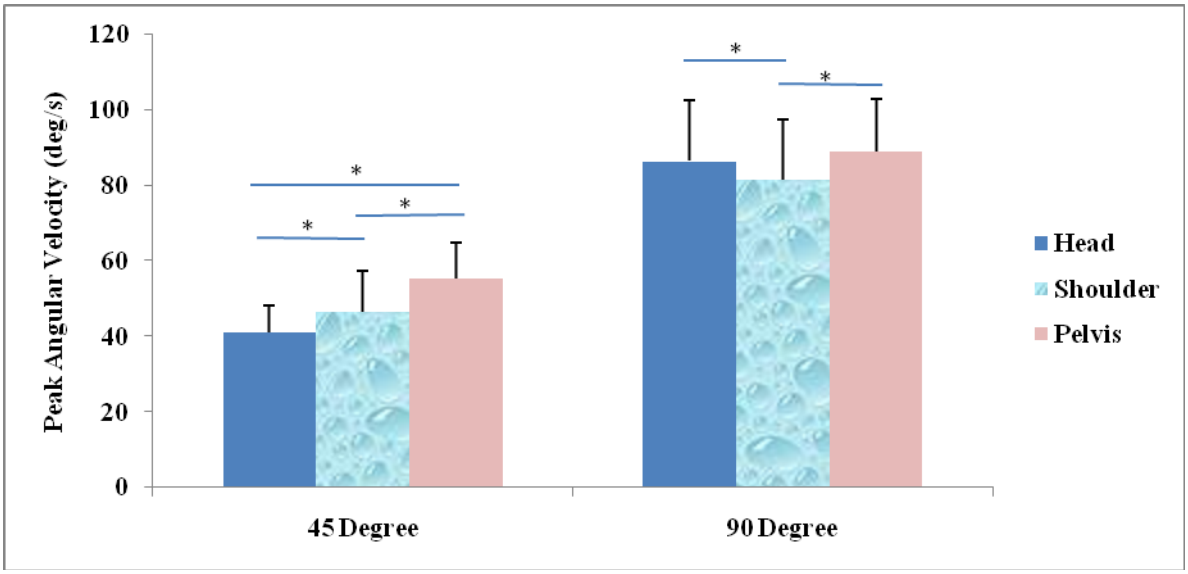


Figure 5.10. Mean and standard deviation (error bars) of the peak angular velocity of head, shoulder, and pelvis in yaw plane during 45° and 90° turns embedded in locomotion for PD participants averaged across "off" and "on" medication condition. Stars indicate significant differences (α=0.05).

ANOVA revealed no significant differences in the sequence and timing of the peak angular velocity of shoulder and pelvis. Furthermore, medication condition and magnitude of the turn had no significant main or interaction effect on the sequence and timing of the peak angular velocity of shoulder and pelvis. Mean and standard deviation of the latencies of the peak angular velocity of shoulder and pelvis averaged across the two different magnitudes of turn and medication conditions were 115±168 and 147±247ms for shoulder and pelvis, respectively.

5.3.2.3 Magnitude

The three way ANOVA revealed significant effect of segment ($F(2,26)=21.22$, $P<0.0001$), magnitude of the turn ($F(1,13)=78.61$, $P<0.0001$), and segment*magnitude of the turn ($F(2,26)=10.35$, $P=0.0005$) on the amount of turn achieved by the onset of mediolateral foot displacement. Tukey's analyses revealed that for each segment the amount of turn was greater during the 90° turns than 45° turns (mean±std=31.6±10.6 vs. 17.1±6deg for head; 26.9±9.5 vs. 15.1±6.1deg for shoulder; and 22.3±9.3 vs. 12.9±7.1deg for pelvis). Furthermore, at each magnitude of the turn, the amount of turn was significantly different for different body segments, being largest for the head and smallest for the pelvis.

Medication had no significant main or interaction effect on the magnitude of head, shoulder, and pelvis turn achieved by the onset of mediolateral displacement of the leading foot. Averaged across the 45° and 90° turns, the mean and standard deviation of the amount of turn achieved by the onset of mediolateral displacement of the leading foot was 23.7±10.4 and 24.9±12.17deg for head, 20.4±8.8 and 21.7±11deg for shoulder, and 17.3±8.6 and 18±10.6deg for pelvis, for PD participants "off" and "on" medication, respectively.

5.3.2.4 Functional Axial Rotation

Analyses of the Functional Axial Rotation score revealed no difference in the flexibility of the cervico-thoraco-lumbar and thoraco-lumbar spine of the healthy elderly and PD participants. Furthermore, FAR score was not different between PD participants "off" and "on" medication. Mean and standard deviation of the FAR score was 99.5±13.4, 93.8±14.9,

and 91±16deg for the head segment, and 42.8±10.2, 36.4±9.7, and 35.6±11.6deg for shoulders for healthy elderly and PD participants "off" and "on" medication, respectively.

5.4 Discussion

This study examined the effect of Parkinson's disease on the sequence and timing of body segment reorientation during different degrees of walking turns. The potential effect of dopaminergic medications on the aforementioned sequence and timing was also investigated. In addition, the prevalence of the single-step and double-step turns and the participants' preference for step or spin turns when changing direction while walking was examined.

When turning while walking healthy participants reoriented their head first followed by simultaneous rotation of the shoulder and pelvis and lastly the mediolateral displacement of the foot. In PD participants, regardless of the medication condition, reorientation of body segments followed a top-down sequence with significant delay among the onset of reorientation of all body segments. The difference in the sequence of reorientation of body segments between the two groups was due to the significantly longer delay time in the initiation of reorientation of pelvis in PD participants than in healthy controls (Figure 5.4).

We found a top-down sequence with significant delay among the onset of reorientation of all body segments as individuals with PD turned in the middle of their walk. This finding is different from the reports by Ferrarin et al. (2006), Crenna et al. (2007), and Carpinella et al. (2007) that individuals with PD turn their head and upper trunk together followed by rotation of pelvis. The difference could be due to the larger sample in our study (14 vs. 7) which had

a greater range of impairment as demonstrated by the UPDRS score. PD participants in our study were more variable with respect to motor performance and balance difficulty as revealed by their greater range of UPDRS score during both "off" and "on" medication. The mean and standard deviation of the UPDRS score for our participants was 24±9.4 and 16±7.8 while "off" and "on" medication, respectively. The mean and standard deviation of the UPDRS score for PD participants while "on" medication were 14.7±3.9 in Crenna et al. (2007) study and 15.6±3 in Carpinella et al. (2007) study. Although in these studies the UPDRS score of PD participants "off" medication has not been reported, Carpinella et al. reported that their PD participants didn't reveal significant changes in the global motor performances between "off" and "on" medication conditions.

Our findings are in agreement with the results of Mak and colleagues (2008) who demonstrated a similar top-down sequence of reorientation of body segments in a group of PD participants and a group of healthy controls as they made 30° and 60° sudden turns in the middle of their walk. PD participants in Mak et al. study were in stages II and III of Hoehn and Yahr scale and reported experiencing freezing of gait during daily activities. There was no difference between the PD participants and healthy controls in the onset times of head and trunk yaw relative to the turning cue delivery in either 30° or 60° turns. (Mak et al., 2008). Although the relative timing of head and trunk turn were not statistically compared between the two groups, by careful examination of the graphs they do not appear to be different.

Magnitude of the turn had no effect on the sequence and timing of segments' reorientation. This result complements findings of Mak et al. (2008) who also reported no difference in the

onset time of body segments for individuals with PD and healthy elderly between 30° and 60° turns.

For both groups the peak angular velocity (averaged across body segments) was significantly larger during the 90° than the 45° turns indicating faster rotation of the segments during the larger turns. At each magnitude of the turn the peak angular velocity was significantly smaller for PD participants than for healthy participants with the difference between the two groups being greater when larger angular velocity was required, i.e., during the 90° turns. Furthermore, regardless of the magnitude of the turn, the peak angular velocity of each segment was significantly smaller for PD participants than healthy elderly. These findings complement recent findings by Visser et al. who reported smaller trunk's peak yaw and roll angular velocities for individuals with PD in comparison with age-matched healthy controls during self-paced, fast (turning as fast as possible), cued (turning suddenly upon an auditory cue), and dual tasking (turning while engaged in a secondary cognitive task) 180° walking turns (Visser et al., 2007). The lower peak angular velocities in individuals with PD could be due to bradykinesia. Alternatively, they may be the result of a compensatory strategy; individuals with PD may turn slower to produce less body angular momentum to be arrested at the end of the turn. As suggested by Visser et al. (2007), peak yaw angular velocities of trunk during turning while walking may be a useful measure for discriminating individuals with PD from healthy elderly.

In light of the findings of the previous studies that demonstrated under-scaled muscle activity (Berardelli et al., 2001), and reduced range of trunk movements in individuals with PD

(Schenkman et al., 1998; Bridgewater et al., 1998), and studies that suggest basal ganglia's dysfunction affects the amplitude of movements in this patient population (Desmurget et al., 2004; Morris et al., 2005), we expected lower magnitudes of rotation for PD participants than healthy controls. Surprisingly, there was no difference between the two groups in the magnitude of the turn completed by any segment at the onset of mediolateral foot displacement. Averaged across the 45° and 90° turns, the mean and standard deviation of the amount of turn achieved by the onset of mediolateral foot displacement was 27.5±14.2 and 23.7±10.4 for head, 21.9±11.5 and 20.4±8.8 for shoulder, and 19.4±9.1 and 17.3±8.6 for pelvis, for healthy elderly and PD participants, respectively. This finding is in agreement with findings of Huxham and colleagues who reported that individuals with PD are able to adequately rotate their body segments during turning (Huxham et al., 2008). In fact, Huxham and colleagues reported that the magnitude of the turn for different body segments measured at the same distances relative to the turning point was greater in PD participants than in healthy controls.

Medication had no significant effect on the magnitude of head, shoulder, and pelvis turn. Considering that for PD participants "off" medication the magnitude of body segments' turn was not smaller than the comparable values for healthy elderly, lack of medication effect is not surprising.

Although not significant, the percentage of double-step turns was always higher for PD participants than healthy controls. This difference was more marked during the 90° turns. While for both groups the frequency of double-step turns was higher than the frequency of

single-step turns during the 90° turns, this difference was significant only for PD participants. Fuller and colleagues showed that older adults with lower balance confidence are significantly more likely to choose a double-step turn to change the direction of their travel path (Fuller et al., 2007). It is possible that the 90° turns were more challenging for our participants, specially the PD participants; therefore, double-step turns were adopted more frequently during the 90° turns to ensure safety.

Contrary to the reports of diminished spinal flexibility in individuals with PD (Bridgewater et al., 1998; Schenkman et al., 2000; Schenkman et al., 2001), functional axial rotation scores of the PD participants in our study were not different from those of the healthy controls. Even while "off" medication, our PD participants' spinal flexibility was similar to that of the healthy controls. Only three of our PD participants reported one fall each in the six months prior to testing, and only one PD participant experienced freezing while walking. PD participants in this study represent a sample of mild to moderately affected individuals with PD. Therefore, the results cannot be generalized to people more severely affected.

Chapter 6: General Discussion

6.1 Discussion

Falls are the leading cause of injury and accidental death among older adults (Macpherson et al., 2005). Thirty to forty percent of community dwelling elderly aged 65 years and over fall at least once per year (Tinetti at al., 1988; Lord et al., 1994). Falls are also a common problem for individuals with PD: 46% of individuals in advanced stages of PD fall at least once per year, and 33% suffer from 2 or more falls per year (Balash et al., 2005). The frequency of injurious falls is also high in advanced stages of PD (Balash et al., 2005). Falls interfere with the health and well-being of the fallers and are disruptive to the lives of fallers even if they don't cause injury. Fallers avoid certain activities due to fear of subsequent falls (Tinetti et al., 1994; Bloem et al., 2001). Immobility has its own negative physiological and psychological consequences that further diminish the quality of life of the faller.

The aforementioned emphasizes the importance of prevention of falls in healthy elderly and individuals with PD. Essential to the prevention of falls is identifying and subsequently removing the factors that contribute to the falls. Many of the falls among healthy elderly and individuals with PD occur during turning. In healthy elderly falling while turning is 7.9 times more likely to cause a hip fracture than falling while walking straight ahead (Cumming and Klineberg, 1994). In individuals with PD abnormal protective arm movements necessary to break the fall by an outstretched hand or by grabbing an external support (Carpenter et al., 2004) may further increase the incidence of a hip fracture in the event of a fall (Bloem et al., 2003). Report of turning difficulty is a sensitive predictor of the two key symptoms of PD locomotion: freezing and falling (Stack et al., 2006).

The underlying causes of deterioration of balance in healthy elderly and individuals with PD during turning are not completely known. Turning is a challenging component of locomotion that requires anticipatory postural adjustments (Xu et al., 2004), systematic reorientation of axial body segments towards the new direction of travel (Patla et al., 1999), and systematic modification of the basic gait parameters (i.e., asymmetric step length and ground reaction forces) (Orendurff et al., 2006; Courtine and Schieppati, 2003). Failure in making any of the above adjustments compromises balance and may result in falls. The purpose of this thesis was to examine the coordination of reorientation of axial body segments during turning in healthy elderly and individuals with PD and to investigate whether the turning difficulty in older adults and individuals with PD is due to the lack of coordination in reorientation of head, shoulder, pelvis, and feet during turning.

Study 1 examined the body segment coordination of healthy older adults during on-the-spot turns and turns embedded in locomotion to determine whether the coordination pattern for turning differs when standing and walking. Incorporating two different degrees of turn in the protocol allowed examining the effect of amplitude of turning on segment coordination. Results of study 1 revealed differences in coordination patterns of on-the-spot turns and walking turns in healthy older adults. During the on-the-spot turns, healthy older adults reoriented their head, shoulder, and pelvis in unison. The simultaneous reorientation of head and trunk was followed by mediolateral foot displacement. This coordination pattern was observed for both small and large turns. These results differ from the results of the studies on healthy young adults that show a top-down temporal sequence in body segment rotation

during discrete (Hollands et al., 2004) and continuous (Earhart and Hong, 2006) on-the-spot turns. The simultaneous rotation of the head and body in healthy elderly may be an adaptive strategy to simplify the control of movement by reducing the degrees of freedom. Grasso and colleagues observed "en bloc" rotation of head and body as young children turned a 90° corner and attributed it to reducing the degrees of freedom to ease control of movement (Grasso et al., 1998). However, whether such strategy enhances or compromises the postural balance of older adults requires further investigation. Future studies should examine the coordination of body segments in healthy older adults and older adults with a history of frequent falls to determine whether a similar strategy is used by both groups. If, unlike healthy older adults, elderly fallers show a top-down temporal sequence similar to the healthy young, it could be concluded that adopting a simultaneous reorientation of head and trunk does improve postural balance in older adults and the inability of elderly fallers to adopt such strategy contributes to the frequent loss of balance and falls during turning in this population.

When turning while walking, healthy elderly displayed a top-down temporal sequence similar to that reported for healthy young adults (Grasso et al., 1998; Patla et al., 1999; Hollands et al., 2001), i.e., the head turned first, followed by the shoulder and pelvis, and finally mediolateral foot displacement. This is a robust behavior which was not affected by the magnitude of the turn. It is possible that during on-line steering, since different body segments are already in motion, simultaneous segment rotation may interfere with the ongoing locomotion; therefore, such strategy was not adopted by our participants during walking turns. Furthermore, the anticipatory reorientation of the head during on-line steering

may provide the central nervous system with allocentric and egocentric reference frames that can be used for effective subsequent reorientation of other body segments (Grasso et al., 1998; Hollands et al., 2001). The aforementioned hypothesis is supported by several neurophysiological studies that have reported existence of "head-direction cells" in the brain of rats (Blair and Sharp, 1995; Mizumori et al., 1993; Taube et al., 1995; Taube et al., 1990) and primates (Robertson et al., 1999). The "head-direction cells" are known to fire selectively when the animal's head is facing in a specific direction in space. The population of "head-direction cells" provides a continuous indication of the animal's directional heading (Blair and Sharp, 1995). The anticipatory reorientation of the head provides the central nervous system with allocentric and egocentric reference frames which may be more critical during walking turns.

Although the sequence of reorientation of body segments during walking turns in healthy elderly was similar to that of the healthy young adults, the delay times in rotation of shoulder and pelvis relative to the head turn were smaller for healthy elderly than what has been reported for healthy young adults. This finding indicates a tighter control of head and trunk during walking turns in healthy elderly in comparison with healthy young adults.

Even though magnitude of the turn did not affect the segment coordination during standing and walking turns, it did affect the angular velocity of the segments. In both conditions and for all body segments the peak angular velocity was greater for 90° turns than 45° turns. Furthermore, in both conditions the peak velocity of head was greater and was reached

earlier than the peak velocity of shoulder and pelvis. These findings indicate that during both standing and walking turns the head turned faster than the other segments.

Both ageing and Parkinson's disease are accompanied by slowing of gait (Öberg et al., 1993; Morris et al., 1994; Morris et al., 1996) which may influence the coordination of walking turns. Therefore, in study 2 we examined the effect of walking velocity on turning performance of healthy older adults. The aim was to determine whether modifications of walking velocity in the absence of any neurological impairment influence the segment coordination during turning. Results of the 2nd study assist the interpretation of any differences that we might find in performance of PD participants and healthy elderly in the 3rd and 4th studies, i.e., we would know to what extent the differences are accounted for by the differences in the gait velocity of the two groups and to what extent they are the direct result of the disease. In study 2 we also investigated if healthy elderly prefer to make a step turn or a spin turn as they turn in the middle of their walk and whether the turn type (step vs. spin) affects the timing and sequence of reorientation of different body segments.

Results revealed that walking velocity does not affect the coordination of body segment reorientation in healthy elderly. Body segment reorientation followed a similar top-down sequence as participants walked at slow, natural, and fast walking speeds. Furthermore, regardless of the magnitude of the turn and the velocity of walking healthy elderly showed no preference in making a step or spin turn. Nonetheless, the timing and sequence of reorientation of different body segments towards the new direction of travel was independent of the turn type. This result complements the findings of Paquette et al. (2008) who reported

no significant effect of turn type on the sequence and timing of segment reorientation for both healthy young and elderly individuals as they approached the turning point.

Spin turns were frequent among older adults in our study. The high frequency of falling while turning in older adults may simply be due to the high frequency of the spin turns. Spin turns are less stable and biomechanically more costly than step turns (Patla et al., 1991; Taylor et al., 2005). During a step turn the COM remains within the base of support for almost the entire duration of the stance phase. During a spin turn however, the COM trajectory falls outside the base of support for a significant duration of the stance phase. This difference is due to the wider base of support during the step turns than spin turns. Furthermore, the step turn requires increasing the activity level of the already activated muscles; the spin turn however, requires inhibiting one group of muscles and activating another group and increasing the magnitude of activity in these newly recruited muscles to an appropriate level (Patla et al., 1991; Taylor et al., 2005). In comparison with the step turns, spin turns require greater range of motion of the lower limb joints in the transverse plane (Taylor et al., 2005). Also, the toe-to-toe distance, which is negatively related to the possibility of interference between the feet and the chance of tripping, is much smaller during the spin turns than during the step turns (Taylor et al., 2005). Therefore, spin turns impose a greater challenge to the locomotor system than step turns. We found that in healthy elderly, regardless of the velocity and magnitude of the turn, spin turns are as frequent as step turns. Considering the high incidence of turning in activities of daily living (Glaister et al., 2007), and the inherent advantages of step turn over spin turn (Patla et al., 1991; Taylor et al., 2005)

instructions on proper turning may reduce the risk of loss of balance and fall during turning and should be included in gait retraining programs.

Postural instability is one of the cardinal symptoms of Parkinson's disease that has a major effect on the quality of life of individuals with PD since it increases the incidence of loss of balance and falls. It is well-known that postural instability of individuals with PD is exaggerated in specific circumstances. For example, individuals with PD show poorer balance and greater incidence of falls while turning (Giladi et al., 1992; Bloem et al., 2001). Freezing while turning is also very common in PD (Giladi et al., 1992). The association of turning with falls and freezing in individuals with PD (Giladi et al., 1992; Bloem et al., 2001; Stack et al., 2006) highlights the importance of understanding the turning impairment in this patient population. In studies 3 and 4 we examined the effects of Parkinson's disease on body segment coordination during the on-the-spot turns and turns embedded in locomotion. The possible effect of dopamine-replacement medications on turning performance of individuals with PD was examined by testing the PD participants "off" and "on" dopaminergic medications.

Our study was the first to examine the coordination of body segment reorientation in individuals with Parkinson's disease during on-the-spot turns and showed that the sequence and timing of body segment reorientation in PD participants ("off" and "on" medication) was similar to that of the age-matched healthy older adults during the on-the-spot turns. Vaugoyeau and colleagues (2006) studied segment reorientation of individuals with PD as they made a single 45° diagonal step while changing their body orientation and reported a

significant delay between the onset of rotation of shoulders and pelvis. The different findings of our study could be due to the differences in the methodology. Participants in Vaugoyeau and colleagues' study were instructed to take a step as they turned. Our participants were not required to take a step; they were simply instructed to turn while standing on the same spot. It should be noted that findings of Vaugoyeau et al. were different from our findings even for reorientation of body segments in healthy elderly.

Segment coordination during walking turns was similar for our PD participants ("off" and "on" medication) and healthy elderly; a similar top-down sequence was observed for both groups. Our results differ from reports by Ferrarin et al. (2006), Crenna et al. (2007), and Carpinella et al. (2007) that showed individuals with PD turn their head and upper trunk together followed by rotation of pelvis. Differences in characteristics of the PD participants may have contributed to the different findings. PD participants in our study displayed a greater range with respect to motor performance and balance difficulty as revealed by their greater range of UPDRS score during both "off" and "on" medication. The mean and standard deviation of the UPDRS score for our participants was 24±9.4 and 16±7.8 while "off" and "on" medication, respectively. The mean and standard deviation of the UPDRS score for PD participants while "on" medication was 14.7±3.9 in Crenna et al. (2007) study and 15.6±3 in Carpinella et al. (2007) study. Although in these studies the UPDRS score of PD participants "off" medication has not been reported, Carpinella et al. reported that their PD participants didn't reveal significant changes in the global motor performances between

"off" and "on" medication conditions, and did not show any treatment side-effect such as dyskinesia.

Our findings are in agreement with the results of Mak and colleagues (2008) who demonstrated a similar top-down sequence of reorientation of body segments in a group of PD participants and a group of healthy controls as they made 30° and 60° sudden turns in the middle of their walk. PD participants in Mak et al. study were in stages II and III of Hoehn and Yahr scale and reported experiencing freezing of gait during daily activities. There was no difference between the PD participants and healthy controls in the onset times of head and trunk yaw relative to the turning cue delivery in either 30° or 60° turns (Mak et al., 2008). Although the relative timing of head and trunk turn were not statistically compared between the two groups, by careful examination of the graphs they do not appear to be different. The larger sample of PD participants in our study (14 people) and Mak et al. study (10 people) in comparison with studies by Crenna et al. (2007) and Carpinella et al. (2007) (7 people) gives us confidence that the behavior reported is an accurate reflection of PD population "off" and "on" medication.

In our study PD participants ("off" and "on" medication) differed from healthy older adults with respect to the velocity and magnitude of reorientation of body segments. The peak angular velocity of each body segment was significantly smaller for PD participants than the healthy older adults during both standing and walking turns. This was observed for both small and large turns. Similar results have been reported by Visser et al. (2007) who demonstrated that the trunk's peak yaw and roll angular velocities are smaller in individuals

with PD in comparison with age-matched healthy controls during self-paced, fast (turning as fast as possible), cued (turning suddenly upon an auditory cue), and dual tasking (turning while engaged in a secondary cognitive task) 180° walking turns. The lower peak angular velocity in PD participants could be due to bradykinesia. Alternatively, it might be a compensatory strategy; PD participants may turn slower to produce less body angular momentum to be arrested at the end of the turn.

The magnitude of reorientation of each body segment was measured at the onset of mediolateral foot displacement. This measure revealed significantly smaller head and trunk rotations for PD participants versus healthy older adults during standing turns, but not walking turns. Contrary to the reports of diminished spinal flexibility in individuals with PD (Bridgewater et al., 1998; Schenkman et al., 2000; Schenkman et al., 2001), functional axial rotation scores of our PD participants were not different from those of the healthy controls even when PD participants were "off" medication. Therefore, mechanical deficits cannot explain the smaller head and shoulder turns in our PD participants during the on-the-spot turns. The smaller amount of turn achieved by PD participants could be due to their lower angular velocity. Alternatively, smaller turns could be the direct result of PD. The role of basal ganglia in scaling the amplitude of movement is well documented (kandel et al., 2000; Desmurget et al., 2004; Morris et al., 2005). In healthy brain, the two parallel direct and indirect pathways coming from striatum modulate the inhibitory effects of the internal globus pallidus on its target nuclei in thalamus and the brain stem. During a voluntary movement, the indirect pathway may assist in braking or smoothing the movement while the direct

pathway simultaneously facilitates the movement. This reciprocal regulation allows scaling the amplitude or velocity of the movement (Kandel, Schwartz, and Jessell, 2000). Desmurget and colleagues (2004) measured the reaction times of individuals with Parkinson's disease and healthy controls as they pointed to a target on a computer screen. The pointing task was performed either without any advance cue or with cue to assist the participants in planning the amplitude or direction of the movement. Results showed that regardless of the cue condition, individuals with PD had longer reaction times than healthy controls. Furthermore, while healthy controls were able to reduce their reaction times to the same extent using either the amplitude cue or the direction cue, individuals with PD had difficulty using the amplitude cue (Desmurget et al., 2004). Considering that impairments in PD are not restricted to the basal ganglia, Desmurget et al. performed a follow up study to specify the anatomical structures responsible for the inability of PD participants in using the amplitude cue. In this study, using positron emission tomography Desmurget and colleagues monitored the activity of the basal ganglia in a group of healthy individuals as they performed the same pointing task under the same cue conditions. Enhanced activation of basal ganglia structures during the magnitude cue condition in comparison with the direction cue and no-cue conditions supports the direct contribution of the basal ganglia to the control of the magnitude of the movement (Desmurget et al., 2004).

Why were the magnitudes of the turn at the onset of mediolateral foot displacement smaller in participants with PD than healthy controls during the standing turns but not during the walking turns? Unlike the walking turns, the standing turns require transition from a static

state to a dynamic state and reorientation of the body either simultaneously or in rapid succession. The transition from static to dynamic state is compromised in both healthy elderly and individuals with Parkinson's disease; however, the deficits are much exaggerated in individuals with PD (Halliday et al., 1998). Halliday and colleagues showed that during quiet stance in comparison with healthy older adults, individuals with PD stand with their center of pressure significantly further ahead of their ankle joints. This in part can be explained by the stooped posture of individuals with PD. During gait initiation the backward and mediolateral movements of the center of pressure were slower and smaller in individuals with PD than in healthy age-matched controls. Furthermore, the velocity of the body center of mass during gait initiation was significantly smaller in PD than in healthy older adults. Martin et al. (2002) also reported that during gait initiation the ability to separate the center of pressure from the center of mass at the preparatory stage of gait initiation is diminished in individuals with PD. In comparison with healthy older adults, individuals with PD showed smaller distance between center of mass and center of pressure throughout the gait initiation (Martin et al., 2002). The slower and smaller movements of the center of pressure and slower movement of the center of mass during the transition from static to dynamic state may account for the smaller turn of all body segments at the onset of mediolateral foot displacement during the standing turns. Abnormalities in the electromyographic activities of the lower limb muscles during gait initiation have also been reported for individuals with Parkinson's disease (Crenna et al., 1990; Gantchev et al., 1996). Gantchev and colleagues showed that in comparison with healthy age-matched controls, in individuals with PD the

activity of Tibialis Anterior (TA) and Vastus Lateralis (VL) during the postural phase of gait initiation, i.e., the time between the initial shift of the center of pressure and the onset of the first step, is reduced. Also, individuals with PD often showed asymmetric or even unilateral activities of TA and VL muscles. Furthermore, the activity of the Gostrocnemius muscles at the end of the postural phase which is responsible for initiating the subsequent heel-off was either absent or replaced by an earlier, prolonged burst (Gantchev et al., 1996). Similar abnormalities may exist during the standing turns and may affect the anticipatory postural adjustments prior to the turn which may influence the subsequent segment reorientation. These speculations however, warrant further examination.

Reduced magnitude of head rotation during the initial stage of the turn limits the individual's ability to visually screen the target during the standing turns, and the target and the travel path during the walking turns. Missing an obstacle or an unsafe surface such as an icy patch within the travel path may lead to loss of balance and fall; therefore, scanning the travel path during walking turns may be more important than scanning the target during the standing turns. The aforementioned may provide an alternative explanation for the smaller magnitudes of the turn at the onset of mediolateral foot displacement in individuals with PD during the standing turns but not during the walking turns. It is possible that it is functionally more important to start the walking turns with larger rotations of body segments, especially the head.

Medication had no significant effect on the temporal or spatial parameters of body segment coordination during standing and walking turns. Nonetheless, considering that for our

participants with Parkinson's disease the coordination of segment reorientation during standing and walking turns was not different from that of the healthy older adults even when they were "off" medication, the lack of effect of dopaminergic medication is not surprising. Medication increased the magnitude of head turn during the 90° standing turns; nevertheless, the magnitude of head turn remained smaller than that of healthy older adults. Previous research has also shown that dopaminergic medications do not change the segmental stabilization during straight walking in individuals with PD (Mesure et al., 1999). Stability of measures of balance and mobility of individuals with PD over the medication cycles, despite the reduced perceived difficulty with daily tasks during the peak dose of medication, has been previously reported (Campbell et al., 2003).

Benjjani and colleagues (2000) showed that levodopa is less effective in alleviating axial signs (such as postural balance and gait) and more effective in reducing the symptoms in the limbs (such as akinesia, rigidity, and tremor). They examined motor performance of ten individuals with severe idiopathic Parkinson's disease who had bilateral Subthalamic Nucleus (STN) stimulation. Participants were examined before and six months after the surgery both "off" and "on" dopaminergic medication. In addition to total motor improvement (changes in the score on the motor component of the UPDRS), improvements in the axial signs (sub-scores for neck rigidity, rising from a chair, balance, posture, gait) and the limb signs (sub-scores for limb akinesia, rigidity, and tremor) were evaluated separately. Results showed that in general the combination of STN stimulation and levodopa administration produced greater motor improvement than levodopa or STN stimulation

alone. Stimulation of STN, alone or in combination with levodopa, did not result in any additional improvement in limb signs in comparison with administration of levodopa alone. However, the combination of these two therapeutic approaches resulted in significantly greater improvement in the axial motor performance of participants in comparison with either levodopa or STN stimulation alone (Benjjani et al., 2000). The synergistic effect of levodopa and STN stimulation suggests that the two therapeutic interventions may work through two different pathways. Neural degeneration in Parkinson's disease may not be limited to dopaminergic pathways. Rather, both dopaminergic and non-dopaminergic lesions may be responsible for postural symptoms of Parkinson's disease, with the non-dopaminergic pathway having a greater effect. Since dopaminergic medications work only through dopaminergic pathways, they cannot alleviate the postural symptoms. In a prospective assessment of falls in a group of individuals with Parkinson's disease, the majority of participants who reported loss of balance and fall also reported that their symptoms were well controlled by their dopaminergic medications when the fall happened, providing support for the notion that postural instability in PD is resistant to pharmacological treatment (Bloem et al., 2001). In fact, levodopa and other dopamine agonists may even increase the incidence of fall in individuals with Parkinson's disease since they improve mobility by alleviating other symptoms without improving balance and stability (Bloem et al., 2001). STN stimulation may alleviate the symptoms resulting from lesions in both dopaminergic and non-dopaminergic pathways. It has been proposed that in addition to its positive effect on dopaminergic pathways, STN stimulation modulates the non-dopaminergic connections

between pedunculopontine nucleus and the basal ganglia (Benjjani et al., 2000). Pedunculopontine nucleus is known to be involved in relaying information regarding postural control. In PD, the basal ganglia have an abnormally exaggerated inhibitory effect on pedunculopontine nucleus (Kandel, Schwartz, and Jessell, 2000). STN Stimulation brings back the system to its normal function by blocking this abnormal inhibitory effect (Benjjani et al., 2000).

Vrancken and colleagues (2005) examined the effects of bilateral STN stimulation on stance and gait performance of fourteen individuals with Parkinson's disease. PD participants were tested with STN stimulator "off" and "on", always after supramximal levodopa dosage. Twenty age and gender matched healthy individuals were also examined as the control group. Participants' performance was examined during quiet stance on a firm surface and on a foam support surface with their eyes open and closed, during the retropulsion test, walking 3 meters with eyes closed, walking up and down a set of stairs, and rising from a chair. Trunk sway and angular velocity in pitch and roll planes were measured using the SwayStar system. Results showed that bilateral STN stimulation improved several drug-resistant stance and gait impairments of individuals with PD. For example, it reduced the 5 Hz tremor in both pitch and roll planes and for all stance tasks. It also decreased the trunk roll amplitude in all tasks indicating improved stability. However, STN stimulation did not improve all features of gait and balance. It did not affect the trunk angular velocities during the retropulsion test, walking with eyes closed and walking up and down the stairs. Although there was a trend for decrease in trunk roll during the retropulsion test when STN stimulator was "on", STN

stimulation did not improve the general recovery strategies. Authors concluded that some axial deficits in individuals with PD are resistant even to a combination of optimal dopaminergic treatment and STN stimulation (Vrancken et al., 2005).

We hypothesized that the lack of coordination in segment reorientation contributes to loss of balance and falls in older adults and individuals with PD during standing and walking turns. However, our findings do not support our hypothesis. Certain factors may have contributed to our findings and should be examined in the future studies. We examined a sample of healthy, physically active older adults with no history of falls. We might have found different results if we had tested a group of elderly fallers. Also, of the individuals with Parkinson's disease who participated in our study only 3 reported one fall each during the six months prior to the experiment. The criterion for inclusion in the faller category for older adults is a self-report of two or more falls in a six months period (Shumway_Cook et al., 1997). Therefore, none of our PD participants are considered fallers. Furthermore, only one PD participant reported freezing of gait. Again, we may have found different results if we had examined the performance of individuals with PD with the history of frequent falls or freezing. Plotnik and colleagues (2005) examined the gait asymmetry of two groups of individuals with PD: PD freezers (n=24) and PD non-freezers (n=12), "off" and "on" dopaminergic medication. Results showed asymmetric gait for both groups as they walked on a straight path while "off" medication; however, gait asymmetry was larger in PD participants who experienced freezing of gait than in PD non-freezers. Although dopaminergic medications elicited more symmetric gait in both groups, this effect was not

significant. Gait asymmetry remained larger for PD freezers than PD non-freezers even when they were "on" medication (Plotnik et al., 2005). Turning requires asymmetric coordination of the lower limbs (Orendurff et al., 2006; Courtine and Schieppati, 2003). Therefore, it is reasonable to expect further decrement in turning behavior of freezers than non-freezers. For example, if a PD freezer who has longer swing time of the left limb during straight walking attempts to turn to the left which requires longer swing time of the right limb, he/she may experience greater difficulty compared with an individual who does not have the baseline gait asymmetry. Nevertheless, Mak and colleagues (2008) report no difference in the timing and sequence of head and trunk reorientation between PD freezers and healthy controls as they made sudden 30° and 60° turns during walking. PD participants were in stages II and III of Hoehn and Yahr scale and reported experiencing freezing of gait during daily activities. PD participants were tested "on" medication. Regardless of the magnitude of the turn, PD participants turned slower with narrower steps and demonstrated a longer delay in initiation of the mediolateral foot displacement. However, there was no difference between the two groups in the onset times of head and trunk yaw relative to the turning cue delivery in either 30° or 60° turns (Mak et al., 2008). Although the relative timing of head and trunk turn were not statistically compared between the two groups, by careful examination of the graphs they do not appear to be different. Authors concluded that the main problem of individuals with PD during sudden turns lies in their inability to rapidly change the motor programs required for straight walking to turning, and this problem is independent of the magnitude of the turn (Mak et al., 2008).

The nature of the turning task may have also affected our findings. Our participants were asked to turn in an open area, with no object or pole at the turning point. Have we examined the turning performance of our participants as they turned around an object, we might have found different results. Recently, Gérin_Lajoie and colleagues (2006) have shown that in comparison with young adults, healthy older adults require greater personal space to circumvent an obstacle positioned on their path. If we have instructed our participants to turn around an object, they might have become concerned about bumping into the object, and therefore have attempted to leave more space between themselves and the object as they turned around it. The aforementioned might have elicited a different coordination of segment reorientation.

Gérin_Lajoie et al. (2006) also showed that attentional demands of circumventing around obstacles are greater for healthy elderly than healthy young adults. While circumventing around an obstacle, healthy older adults made significantly more mistakes on the concurrent cognitive task than healthy young adults. Therefore, asking our participants to turn around an object may increase the cognitive load of the turning task, subsequently affecting their performance. In our study, before starting with the turning trials we asked each participant to walk around a set of pylons which were arranged on the lab floor in a way that it required the participant to make either 90° or 135° turns in order to circumvent them. Each participant walked three times along such paths for a total of six trials. Our only PD participant with the history of freezing of gait experienced freezing as he circumvented the pylons during all six trials. However, he did not experience freezing during any of the walking turn trials. Very

different behavior of this participant as he turned around an object (a pylon) or on an open area provides further support for the notion that turning around something or around a corner may elicit different strategy than turning on an open area. This is an important issue that requires further investigation.

In real life situations turning is rarely performed in isolation. For example we turn as we talk to a friend, or in the kitchen while carrying a food item from refrigerator to the dinner table. A concurrent manual or cognitive task has been shown to deteriorate functional mobility in elderly population (Shumway-cook et al., 2000). In comparison with healthy elderly, postural control of individuals with PD suffers more during dual task conditions due to their inability to prioritize the postural task over the concurrent cognitive or motor task (Bloem et al., 2006). Future work should examine the effect of concurrent cognitive and motor tasks on turning execution of healthy elderly and individuals with PD.

The basal ganglia are involved not only in the execution but also in the preparation for movement. Presentation of a cue that specifies the direction of the limb movement to be executed changes the discharge rate of some neurons in the premotor cortex, supplementary motor area and motor cortex within the skeletomotor circuit. These changes in the discharge rate which linger until the movement is initiated indicate involvement of this circuit in the preparatory aspect of the motor control or the "motor set" (Kandel et al., 2000). Therefore, basal ganglia disorders could compromise both the planning and execution of the movement. Limiting the planning and execution time by postponing the signal to turn could have a negative effect on performance of the individuals with PD during turning. This effect

however, was not examined in the present study. For each trial the direction of the turn was specified before the trial was started; therefore, our participants had advance knowledge of the direction and magnitude of the turn and sufficient time to plan and execute their turn. We may have found different results if we had limited the planning and execution time by postponing the cue regarding the direction and magnitude of the turn, especially for the larger turns which require greater changes of the locomotor pattern. Nevertheless, a recent study by Mak and colleagues (2008) did not reveal any effect of delayed cue on the coordination of the body segments reorientation during the walking turns. Mak et al. examined the performance of individuals with PD and healthy controls as they made sudden 30° and 60° right and left turns during walking. The cue to turn was given two steps prior to the turn which is the least time required even by healthy young adults to successfully complete a turn (Patla et al., 1991). In agreement with the results of our study, Mak and colleagues found no difference in the timing and sequence of head, trunk reorientation between healthy elderly and individuals with PD during turning (Mak et al., 2008). The greater incidence of fall and freezing in individuals with PD during turning could be due to their inability to modify the motor plan from straight walking to turning. Also, turning while walking is a challenging component of locomotion that requires translation and rotation of the body towards the new direction of travel while maintaining dynamic stability (Patla et al., 1991). Turning imposes changes in both anterior-posterior and mediolateral impulses in order to slow the locomotion speed along the sagittal plane and move the COM towards the new direction of travel (Patla et al., 1991). It necessitates asymmetric tuning of the step lengths and ground reaction forces

to redirect the cyclical movement of the lower limbs (Orendurff et al., 2006; Courtine and Schieppati, 2003). Failure to integrate the aforementioned control mechanisms results in increased difficulty in turning and consequently greater risk of fall. Using positron emission tomography scanning Malouin et al. (2003) examined the pattern of brain activation when individuals imagined themselves performing various locomotor tasks, e.g. standing, gait initiation, walking, and walking through a series of narrow passages. Results showed that as the cognitive and sensory information processing demands of the task increased progressively more areas of the brain became activated (Malouin et al., 2003). It is possible that due to the greater integration load of the turning task and greater involvement of the higher levels of the central nervous system during turning, turning is more susceptible to impairment than linear walking.

Due to the limited equipment and space we were not able to examine the effect of direction of turn on the segment coordination. Considering that healthy individuals demonstrate directional preference during the spontaneous turns (Yazgan et al., 1996; Lenoir et al., 2006; Taylor et al, 2007), and the asymmetric nature of Parkinson's disease (Samii et al., 2004; Djaldetti et al., 2006) future studies should examine the effect of direction of turn on timing and sequence of reorientation of body segments in both healthy elderly and individuals with PD.

Even though Parkinson's disease had no significant effect on the relative timing of body segment reorientation in our PD participants, it may have caused a global delay in initiation of reorientation of all body segments. In PD participants, initiation of the head turn may have

been significantly delayed while the delays in the initiation of rotation of the body segments relative to the head turn remained similar to the comparable values in healthy older adults. Nonetheless, the present protocol does not allow examining this effect. Furthermore, PD participants in this study represent a sample of mild to moderately affected patients. Therefore, the results should not be generalized to patients more severely affected.

Lack of a group of healthy young adults as the control group is another limitation of this study. Performance of healthy elderly is compared with the reports of the performance of healthy young adults in the literature. Nevertheless, different methodological approaches may account for some differences in the results.

6.2 Conclusion

In healthy older adults the multi-segmental coordination patterns differ for on-the-spot turns and walking turns. During the on-the-spot turns this coordination pattern is different from the top-down temporal sequence reported for healthy young adults. When turning while standing healthy elderly turn their head, shoulder, and pelvis in unison followed by mediolateral foot displacement. This coordination pattern is independent of the magnitude of the turn.

The sequence of reorientation of body segments during turns embedded in locomotion in healthy older adults is similar to what has been reported for healthy young, i.e., rotation of body segments proceeds from the head to shoulder, pelvis, and feet. This coordination pattern is independent of the walking velocity and magnitude of the turn. We conclude that the top-down sequence in body segments reorientation during walking turns is a robust phenomenon that does not depend on age, turn type, walking velocity, and magnitude of the turn.

The sequence and timing of body segment reorientation remain intact in Parkinson's disease. Parkinson's disease however, reduces the velocity of reorientation of each body segment during both standing and walking turns. Parkinson's disease also reduces the early magnitude of reorientation of each body segment during the on-the-spot turns. These spatial parameters are not improved with dopamine-replacement medication.

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