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The effects of constraining head rotation on eye and whole-body coordination during standing turns at different speeds

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Abstract

A limitation of the ability to rotate the head with respect to the upper body, has been associated with turning problems, however, the extent of head constraints on whole-body coordination has not been fully determined. The aim of this study was to limit head on body rotation and observe the effects on whole-body coordination during standing turns at various speeds. Twelve participants completed standing turns at 180 degrees. A Vicon motion system and a Bluegain electrooculography system were used to record movement kinematics and measure horizontal eye movements, respectively. All participants were tested at three randomised speeds, and under two conditions with or without their head constrained using a head, neck and chest brace which restricted neck movement. A repeated measures ANOVA found a significant main effect of turning speed on the onset latency of all segments, peak head-thorax angular separation and step characteristics. Constraining the head rotation had multiple significant effects including; delayed onset latency and decreased intersegmental coordination defined as peak head segmental angular separations, increased total step and step duration, and decreased step size. This indicates the contribution of speed, head and neck constraints, which have been associated with falls during turning and whole-body coordination.

Keywords: constraining head, turning, whole-body coordination, eye movement

Word Counts: 4,000

Introduction

Turning is characterized by a consistent sequence of events usually starting with eye rotation in the direction of the turn followed by the head, upper body and finally the feet.[1-3] Previous studies suggest that anticipatory eye movements that normally precede rotations of the head and lower body play an important role in prompting the typical top-down reorientation sequence in healthy adults.[1-3] Furthermore, the timing and nature of eye movements and the characteristics of the relative rotation between body segments observed during turning is dependent on the speed and size of rotation and the visual context, i.e. whether participants are turning to a visual goal or to a remembered location.[3] These relationships are highly predictable and therefore it is clear that the eye, head and body are all closely coordinated by the central nervous system. In addition, it has been shown that both vision (via the optokinetic reflex) and neck proprioception (cervico-ocular reflex observed in vestibular patients) can also contribute to the generation, and maintenance, of eye nystagmus.[4, 5] Gaze control is an integral and fundamental part of the steering synergy by which one might predict that altering gaze constraints, e.g. by fixing the head to the body, would result in changes to whole-body coordination and stepping characteristics in younger adults. This prediction is supported by the results of Hollands et al. (2001) who showed that experimentally fixing the head with respect to the upper body resulted in changes to the timing of axial segment reorientation during changes in walking direction.[6] However, eye movements were not assessed and therefore the relationships between eye, head and body coordination could not be explored.

Previous research by Reed-Jones and colleagues (2009) found that steering responses could be evoked via rotation of the visual scene.[7] While stepping-in-place, participants viewed a first-person perspective video simulating the visual experience of walking towards and around a corner. The authors showed that significant eye and axial segment rotations were evoked with relative inter-segment timing that was characteristic of real-world voluntary turning, head and body coordination being altered in patient groups with axial rigidity and bradykinesia. In addition, Ambati et al (2013) translated this paradigm to real-world steering by asking participants to walk towards a wall and make a 90° turn under free gaze and fixed gaze conditions.[8] During the fixed gaze condition, participants were required to fixate on a target on the wall until the transition stride of the turn, which effectively suppressed the initiating saccade. When the fixation target reached the limit of the visual field, participants initiated the normal pattern of nystagmus eye movements. Fixed gaze during turn initiation caused a disruption in the sequence of body segment reorientation and turns were initiated in an en-bloc fashion, i.e. the head and body turned together. Furthermore, it has also been observed that the en-bloc strategy while turning is characterized by reduced relative rotations between adjacent segments and a near-simultaneous rotation initiation at reduced turning speeds in older adults compared to younger adults.[9] Subsequently, slowness of body segment movements in response to a trigger suggests that a person will be less well prepared for negotiating mobility safely and thus more likely to trip or fall. This may be adopted to simplify control turning movement patterns and may be an indicator of compensation for decreased postural stability and balance in frail populations during turning.[3] In addition, Robins and Hollands (2017) also showed that the characteristics of whole-body coordination in healthy young participants turning on the spot are systematically related to the speed of turning, with a linear relationship between turning speed and the extent of separation of both the head and body at the start and during the turn.[10] These studies suggest that en-bloc turning, as observed in older adult and patient groups, may be a simple function of slower turning speed.

A deeper understanding of how speed of rotation and head constrained on body rotation affects gaze and whole-body coordination during turning should further elucidate the role of eye and head rotation in turning control. These factors are due to the body having multiple mechanisms to ensure that the eyes lead the head and body rotations during turning. Therefore, the aims of this study were to limit head on body rotation via a neck brace and observe the effects on eye and whole-body coordination during standing turning at various speeds. Our working hypothesis was that anticipatory eye and head rotations normally serve to intermittently anchor gaze on environmental features in advance of the turning body in order to aid stability and guide postural reorganization during the turn. We also hypothesized that a combination of constraining head-on body reorientation and turning at slow speeds would result in an increase of eye movement characteristics and a reduction of intersegmental coordination to adapt in cases of disruption to the normal gaze control and en-bloc axial segment control mechanisms, respectively.

Methods

Study design and participants

Sample size estimates were calculated by using the head onset latency variable from a previous study which used similar methods.[11] A sample size of 12 participants was determined to be sufficient using G-power statistical software (Effect size: f = 1.59, Alpha = 0.05, power = 0.95, sample size = 24, critical t (18) = 2.07, Lambda = 3.89). All participants were asked to read a participant information sheet and sign an informed consent form approved by Liverpool John Moores Research Ethics Committee (REC) (Ref. no. 16/SPS/001). Participants were excluded if they reported any neurological or cognitive impairments, or if they had any current musculoskeletal problems such as fractures or severe pain.

Materials

Thirty-nine reflective spherical markers were attached on the bony prominences of the participants using the Plug-in-Gait marker model and tracked using a Bonita motion analysis system (Vicon Nexus, version 2.4, Oxford, UK) at a sampling frequency of 200Hz. A Bluegain Electrooculography system (Cambridge Research System Ltd.) was used to record horizontal eye movements at a sampling frequency of 1000Hz. A surface electrooculography electrode was placed on the outer canthi of each eye and a reference electrode was placed in the centre of the forehead. A LabVIEW programme was used to control the presentation of visual cues (described below), and synchronise the two data streams via a simultaneously marked time point within the electrooculography data acquisition software and Vicon Link analog input to the Nexus motion data capture system.

Turning protocol and data collection

Participants stood approximately four metres in front of a projector screen (2.74 x 3.66m. Cinefold Projection Sheet, Draper, Inc, Spiceland., Indiana, USA). Data were collected in twelve combinations of three experimental conditions which were as follows;

a. Participants either wore a head, neck and chest brace to constrain head-on body reorientation (Figure 1a) or head was unrestrained.

b. Participants were asked to turn at fast (1.5s), moderate (2s) and slow (3s) speeds as suggested by previous literature on turning 180 degrees.[10, 12]

c. Participants turned either clockwise or counterclockwise.

Prior to each trial, a LabVIEW programme was used to control the visual and auditory cues which projected onto a screen which showed an animation demonstrating the direction and speed in which participants were required to turn, in accordance with one of the experimental conditions (Figure 1b and 1c). Thirty trials for each condition (normal and constrained head conditions) included 10 trials of fast speed (left 5, Right 5), 10 trials of moderate speed (left 5, Right 5) and 10 trials of slow speeds (left 5, Right 5). Therefore, 60 trials were recorded in total for each participant. Trials were organised into six blocks of 10 trials for each condition and counterbalanced across participants. Prior to the testing session, each participant performed a minimum of two practice trials. Participants were told to complete 180 degree turns by imitating the direction and speed of the animated clock arm and audio signal as accurately as possible. In addition, they were told “please begin turning on the first audio signal and finish turning when the audio signal finishes, as precisely as possible”, as has been described previously. In each case the participant’s head, body, and feet finished aligned with the condition of the new travel direction. The practice trials were performed until both the investigator and participant were confident. The reorientation of body segments in each trial were recorded. A 10 minute break at the end of the practice trials and a 2 minute break between trials c were allowed, allowing full recovery after each trial.

[Insert Figure. 1]

Data analysis

The Plug-In-Gait (PiG) model)Vicon©, 2002(was used to determine angular displacement of the head, thorax, pelvis and left and right feet by using a minimum marker set mostly placed on bony landmarks in the global reference frame. In addition, PiG is implicit by shared markers and joint centres between adjacent segments. Subsequently, marker trajectories vectors from raw marker data (Vicon Nexus, version 2.4, Oxford, UK) were used for data analysis. Kinematic data were passed through a dual low-pass fourth-order Butterworth filter using a cut-off frequency of 6Hz. The MATLAB (R2020a) programming environment was used to analyse all measures from the kinematic datasets using the following as dependent variables:

1) Reorientation onset time of eye, head, trunk and feet and peak head-trunk separation as markers of axial segment coordination

2) Amplitude and velocity of yaw trajectory time-series from each body segment

3) Temporal-spatial stepping characteristics (step onset, step frequency, step size, and turn duration)

First, the displacement profiles were differentiated to yield velocity and acceleration profiles for each segment (Supplementary file 2). The criteria used to determine the rotation onset for each segment as the earliest time point preceding segment displacement of 5° that was >0° with a velocity >0° s^{-1}. The end of rotation was determined as the first zero crossing in the velocity profile following the end of the segment rotation (Figure 2). The time-course of the turn trials varied in duration, and therefore, time-normalised profiles were created for the axial segments using the onset and offset latencies from the axial segments (i.e., the head, thorax, and pelvis). The data were normalized to 101 time points in MATLAB between the head yaw onset and the final axial offset. Angular separation profiles were then obtained by subtracting one profile from another, resulting in head–thorax, head–pelvis, and thorax–pelvis profiles.

[Insert Figure. 2]

Individual step characteristics were determined from step onset to step end. Step duration was defined as the interval between step onset and step placement time during the turn. The average step size was measured from the yaw rotation of the foot during the swing phase in each step while turning. The total number of steps during turning was counted from the first step to the completion of the turn. Finally, the step frequency was calculated from the number of steps taken divided by stepping duration (Figure 3). All turning kinematics and stepping characteristics variables were analysed using a previously validated methodology.[10]

[Insert Figure. 3]

Finally, electrooculography calibration was performed before data collection which required the participant to fixate a point on the screen directly in front of them and make slow sinusoidal head movements in the yaw plane, around the vertical axis. Eye position and head position data were temporally aligned and a portion of the data between a peak and a trough of the sinusoidal pattern was selected for calibration analysis. A linear regression model in MATLAB (R2020a) was used to generate an equation which was used to convert electrooculography values measured in mV, to angular displacement of the head in degrees (Supplementary file 1). Bespoke MATLAB (R2020a) scripts were used to obtain all measures from the electrooculography dataset which was also validated by Robins and Hollands (2017).[10] All electrooculography data were dual low-pass filtered using a fourth-order Butterworth filter with a 30Hz cut-off frequency (Figure 4). The differentiation of the eye displacement profile was performed to calculate angular velocity and acceleration profiles.10 For fast phase determination, electrooculography data was inspected alongside head onset and end times, prior to analysis. To eliminate saccades and fixations that occurred prior to, and following, the turn, lower and upper limits were manually determined. From this selection of the data, nystagmus fast phases were determined using time intervals beginning with positive zero crossings and ending with negative zero crossings. Moreover, eccentric eye positions at fast phase onset and end were determined and all individual fast phase amplitudes, velocities and accelerations were gained from fast phase onset to fast phase end time.

[Insert Figure. 4]

Statistical analysis

SPSS statistics version 24 (IBM Corporation, Armonk, NY) was used for all statistical analysis. The data distribution was revealed by a hypothesis test for a test of normality in SPSS. As our sample size was 12 (<50 samples), the Shapiro-Wilk test was used for the analyses. For most of our variables this was not significant suggesting normally distributed data. Therefore, a 2 x 2 x 3 repeated measures analysis of variance (RM ANOVA) was performed on kinematics and eye movement variables with the factors being; direction (left or right), condition (normal or head constraint) and speed (fast, moderate or slow). No effects of direction were found on any measures, therefore, data was collapsed resulting in a 2 x 3 RM ANOVA design. In addition, a further regression analysis between peak head yaw velocity and peak head–pelvis angular segment separation was revealed a correlation of head segmental angular separation between the trunk and pelvis. Statistical significance was set at $P<0.05$. A Bonferroni correction was used for multiple comparisons which set the new alpha at $P<.008$.

Results

Twelve healthy young adults (5 males and 7 females, mean age 23.58±3.15 SD years, mean weight 63.55±10.56 SD kilograms, and mean height 1.66±0.92 SD metres) participated in the study.

Segment reorientation began with the eyes followed by the rotation of the head, trunk and pelvis and, finally, the leading and trailing foot; this sequence was preserved for each turning speed and turning condition (Figure 5a and 5b). No interactions between speed and head constraint conditions were found for any segment onset latency. However, there was a significant main effect of turn speed on mean onset latency for all segments (eye: $F_{(2, 22)} = 5.21$, $P<0.005$, $\eta_p^2 = 0.321$; head: $F_{(2, 22)} = 40.40$, $P<0.001$, $\eta_p^2 = 0.786$; thorax: $F_{(2, 22)} = 46.53$, $P<0.001$, $\eta_p^2 = 0.809$; pelvis: $F_{(2, 22)} = 46.04$, $P<0.001$, $\eta_p^2 = 0.807$; leading foot: $F_{(2, 22)} = 43.25$, $P<0.001$, $\eta_p^2 = 0.847$; trailing foot: $F_{(2, 22)} = 83.91$, $P<0.001$, $\eta_p^2 = 0.868$). With onset latencies being shortest during fast speed trials (eye = 0.55±0.01s, head = 0.56±0.02s, Thorax = 0.57± 0.02s, Pelvis = 0.55±0.02s, leading foot = 0.67±0.03s, and trailing foot = 0.89±0.04s) and longest during slow speed trials (eye = 0.63 ± 0.03s, head = 0.67±0.02s, Thorax = 0.68±0.02s, Pelvis = 0.66±0.02s, leading foot = 0.86±0.03s, and trailing foot = 1.29±0.04s). There was no significant main effect of head constraint for any segment onset latency (Figure 5c).

[Insert Figure. 5]

For intersegmental coordination relationships, there was a significant main effect of turn speed on peak head to thorax angular separation with fast speed = 20.68±2.98°, moderate speed = 12.55±1.72°, slow speed = 9.28±1.28° ($F_{(2, 22)} = 13.42$, $P<0.001$, $\eta_p^2 = 0.582$) and peak head to pelvic angular separation with fast speed = 20.51±3.41°, moderate speed = 13.24±2.15°, slow speed = 11.26±1.35°, ($F(2, 22) = 7.13$, $P<0.005$, $\eta_p^2 = 0.427$), which showed that peak segmental separation increased with an increase in turn speed. In addition, there was a significant main effect of head constraint on peak head-thorax angular separation with fast speed = 1.81±0.27°, moderate speed = 1.36±0.17°, slow speed = 1.35±0.22° ($F_{(1, 11)} = 56.54$, $P<0.001$, $\eta_p^2 = 0.837$) and peak head-pelvic angular separation with fast speed = 5.08±0.76°, moderate speed = 4.17±0.45°, slow speed = 4.13±0.45° ($F_{(1, 11)} = 41.77$, $P<0.001$, $\eta_p^2 = 0.729$) (Figure 6a and 6b), demonstrating that constraining the head restricted head rotation with respect to the rest of the body. Moreover, Figure 6c shows the regression analysis between peak head yaw velocity and peak head to thorax angular segment separation, which revealed the existence of significant positive relationships between the head and thorax under the head unrestrained condition (R^2 = 0.45, P<0.005).

[Insert Figure. 6]

Regarding to eye movements, there were no main effects of turn speed or interaction between turn speed and head condition on fast phase characteristics. There was a significant main effect of head constraint on initial fast phase amplitude with fast speed = 35.84±7.58°, moderate speed = 36.38±9.84°, slow speed = 30.87±10.05° ($F_{(1, 11)}$ = 11.15, P<0.05, η_p2 = 0.503), Figure 7a; and velocity with fast speed = 342.09±86.84°s-1, moderate speed = 364.40±79.04°s-1, slow speed = 331.64±67.92°s-1 ($F_{(1, 11)}$ = 8.52, P<0.05, η_p^2 = 0.437), Figure 7b). This shows the initial fast phase amplitude and velocity were increased in the head constrained compare to the non-restrained condition. Furthermore, there was no effect of turn speed or head constraint on initial gaze shift amplitude when considering the sum of eye plus head rotation (Figure 8c).

[Insert Figure. 7]

Finally, no interaction effects were found between turn speed and turn condition. There was a significant main effect of turn speed on step size with fast speed = 77.29±2.78°, moderate speed = 68.0±2.3°, slow speed = 60.54±2.8° ($F_{(2, 22)}$ = 27.31, P<0.001, η_p^2 = 0.713) and total number of steps taken to turn with fast speed = 3.45±0.11 N, moderate speed = 4.10±0.18 N, slow speed = 4.76±0.24 N, $F_{(2, 22)}$ = 31.49 (P<0.001, η_p^2 = 0.481), Figure 8a and 8b. Furthermore, there was a significant main effect of head constraint on step size with fast speed = 72.23±2.85°, moderate speed = 65.0±1.72°, slow speed = 59.36±2.23° ($F_{(1, 11)}$ = 5.77, *P*<0.005, $\eta_p^2 = 0.344$) and total steps with fast speed 3.52±0.13 N, moderate speed = 4.10±0.17 N, slow speed = 4.84±0.21 N ($F_{(1, 11)} = 27.54$, $P<0.005$, $\eta_p^2 = 0.741$). Post hoc pairwise comparisons revealed that the effects of turn speed were limited to step size, and there were significantly decreased between fast and moderate speeds ($P= 0.001$), fast and slow speeds ($P=0.001$) and moderate and slow speeds ($P=0.011$). Significant effects of head constraint ($P<0.05$) were limited to the step size and there were significantly smaller of step size ($P=0.035$) in the constrained head compared to the unconstrained head conditions. In addition, post hoc tests showed the effects of turn speed were limited to total number of steps, and significant differences were seen between fast and moderate speeds ($P<0.001$), fast and slow speeds ($P<0.001$) and moderate and slow speeds ($P=0.011$), which showed that more steps were made during slow turns than during fast turns, and more steps while making moderate turns than while making fast turns. Furthermore, no interaction effects found between turn speed and turn condition. This showed a main effect of turn speed ($F_{(2, 22)} = 32.66$, $P<0.001$, $\eta_p^2 = 0.748$) and a main effect of turn condition ($F_{(1, 11)} = 9.23$, $P<0.005$, $\eta_p^2 = 0.456$); modelling the constrained head on body reorientation resulted in significantly increased stepping frequency for all turn speeds (Figure 8c).

[Insert Figure. 8]

Discussion

This is the first study to investigate the effects of restricting independent head rotation on eye and whole-body coordination during standing turns at various speeds. We hypothesized that turning at different speeds and in different head constraint scenarios would result in changes in whole-body coordination and characteristics of stepping behaviour. We have accepted our hypotheses as the data shows that both turning slowly and restricting head on body movement, resulted in altered eye movement and changes in whole-body coordination. Our findings are discussed in the context of previous studies of eye, head and body coordination during turning and discuss the implications for understanding turning deficits in clinical populations such as people with PD.

Regarding to the effects of constraining independent head rotation, it is important to note that restricting head on body rotation had no significant effect on the mean turning speed in any of the required turn speed conditions (Figure 4). Therefore, we can rule out the possibility that changes to eye, head and body coordination and stepping characteristics due to restraining head on body rotation are an in indirect consequence of changes to turn speed. For eye movement characteristics, we found that, on average, the eyes led rotation of all other segments (Figure 6). The first gaze shift amplitude (eye reorientation in space) was preserved in the head restrained condition by increasing the amplitude of the first saccadic eye movement (Figure 6a). Considering the finding that the eye movement initiation preceded that of all other segments this suggests that during the initiation of turning, eye and head movements are programmed together in order to shift gaze to a desired eccentric location. It is likely that this gaze shift serves to provide a stable visual anchor that facilitates maintenance of balance during the potentially destabilizing postural reorganization at the onset of the turning movement. Gaze anchoring on salient environmental features via combined head rotations and saccadic eye movements is likely similar to the alternating saccade and fixation strategy employed during manual reaches [13, 14], precision stepping [15, 16], and obstacle crossing.[17] Gaze anchoring could presumably be used to provide the head with an intermittent visual reference point during rotation which may explain why the size and frequency of fast phases are altered when vision are removed.[10, 18] Therefore, compensation of eye movement due to lack of head movement is to achieve this visual reference for initiating and completing the turns. In addition, the effects of constrained head were to reduce step amplitude and increase the number and frequency of steps (Figure 9). Robins and Hollands (2017) showed that fixing gaze with respect to the head in healthy young participants also resulted in reduced stepping frequency.[10] However, it is noteworthy that peak head-thorax separation was also reduced which raises the possibility that altered stepping may have been an indirect consequence of reducing head on body rotations rather than effects of changes in gaze per se. It is interesting to note that activation of neck proprioceptive signals, as induced by prolonged neck muscle vibration or tonic head deviation, has been shown to have a strong influence on gait trajectory orientation [5, 19-21], suggesting that turning can be driven by a proprioceptive drive from neck muscle spindle 1a afferents. In combination, these studies support a role of head on trunk rotation in driving turning.[20, 21] These results raise the possibility that reduced head on trunk, and associated reduction in proprioceptive drive from neck muscle spindles, may contribute towards the observed altered stepping patterns, i.e. the reduced amplitude and increased frequency of stepping movements.

The aim of the study was also to examine the effects of manipulating turning speed on eye, head and whole body coordination during turning in healthy adults. There was a significant main effect of turning speed on the following dependent measures: reorientation onset latency of eye, head thorax and feet, peak head-thorax angular separation, step angular displacement amplitude, step frequency and number of steps.

Firstly, reorientation onset latencies, several previous studies have documented that, when visually cued to turn, individuals with PD take longer to initiate axial segment rotation than neurotypical control participants and suggested that bradykinesia could account for these differences.[3, 22-25] The current results from healthy participants asked to turn at different speeds are in line with these findings; segment reorientation began with the eyes followed by the rotation of the head, trunk and pelvis and, finally, the leading and trailing foot. It is noteworthy that onset latencies for all segments were shortest during fast speed trials and longest during slow speed trials for all segments. Secondly, concurrent axial segment reorientation onset has been used to characterize turning as en-bloc.[3] However, measuring the rotation of the head with respect to the upper body during the duration of the turn gives a more complete description of which body segments lead during the turning motion.[11, 26, 27] Our results clearly show that the head is rotated in advance of the body by up to around 20 degrees on average during fast turns but this reduces to around 10 degrees during slow turns. Furthermore, we showed that the extent of peak head-thorax separation is a linear function of peak head yaw velocity; a proxy of turning speed (Figure 7). This is consistent with the results of Robins and Hollands (2018) who showed a somewhat similar relationship in participants turning with a more limited range of turning speeds.[10] This is an important finding since en-bloc turning has often been described as a consequence of altered ability to coordinate segment rotation in patient populations and older adults.[2, 3, 28] However, our results suggest that reduced separation between segments during turning may represent the disrupted coordination process associated with turning slowly. Indeed, a recent study has also shown reduced head on body separation during a change in walking direction reinforcing the proposal that en-bloc turning in patient populations may, in part, be a function of slow turning.[9] Finally, slow turning was associated with smaller and more frequent steps. Our results suggest that small, frequent steps may also be partially explained by a generalized effect of simply moving slowly. During walking, older adults and individuals with neurological deficits such as individuals with Parkinson's disease generally take rapid, short steps which presumably serve to constrain centre of mass excursions within the reduced base of support formed by keeping the feet closer together, resulting in a shuffling gait disorder. Stack et al. (2008) showed that individuals who had difficulty in turning took more number of steps compared to those who reported no problems in turning, suggesting that shuffling gait may represent a strategy to compensate for actual or perceived instability.[24]

Several previous studies have documented that, when visually cued to turn, older adults or individuals with PD take longer to initiate axial segment rotation and take much longer to turn than neurotypical controls.[3, 22-24, 29] Our findings add weight to these previous studies, our results demonstrating the segment onset latency of turning at slow speed were eye = 0.63 ± 0.03s, head = 0.67±0.02s, thorax = 0.68±0.02s, pelvis = 0.66±0.02s, leading foot = 0.86±0.03s, and trailing foot = 1.29±0.04s. The data are similar to a study by Ashburn et al. (2014) which reported segment onset latencies of individuals with PD during standing turns of 180°, specifically the eye 0.55±0.04s, head 0.53±0.03s, shoulder 0.54±0.03s, pelvis 0.73±0.04s, leading foot 0.93±0.07s and trailing foot 1.48±0.11s. In addition, Anastasopoulos et al. (2011) reported segment onset latency values of the eye = 0.5s, head = 0.6s, trunk = 0.7s and foot 1.1s in individuals with PD during turns of 90°, which were similar to the findings reported by Mak et al. (2008) who showed the onset latency of the head = 0.6s, trunk = 0.7s and the foot first step = 1.2s. Other studies have shown that individuals with PD show differences in their stepping characteristics, with our study showing turning step = 4.84±0.21 N during the slow turn with head constrained, which was similar to Stack et al. (2008) who reported that people with PD took 4.5 turning steps during a 180° standing turn. Our study demonstrated first fast phase amplitude and velocity of 30.87±10.05° and 331.64±67.92°s^{-1}, respectively during the slow turn with head constrained, whereas Lohnes and Earhart (2011) found that individuals with PD demonstrated first fast phase amplitude and velocity = 20.6 ± 8.1° and 219.0 ± 65.6°s^{-1}, respectively. Finally, our study reported peak head-thorax inter-segmental rotation characteristics at slow speed of 9.28±1.28°, whereas Anastasopoulos et al. (2011) reported peak head-trunk in individuals with PD equal to 20-30°.[11, 23-25, 30] Taken together, one conclusion which can be drawn from these studies is that bradykinesia could account for the differences in observed behaviour .Our results indicate that intentional slow turning results in stepping, inter-segmental coordination and eye movement characteristics that are broadly similar to those that have been previously attributed to difficulties in turning in individuals with PD.

Additionally, restraining head and neck movements also altered fast phase characteristics during standing turns. Lohnes and Earhart (2011) reported that people with PD exhibit a greater number of saccades (8.9 ± 3.2N, our study found 6.57 ± 2.33N) during 180° turning and show differences in initial fast phase amplitude and velocity, compared to a control group.[30] These results are relevant to reported disturbances in eye characteristics of individuals with PD during turning. They suggested that saccadic eye movement dysfunction due to PD neuropathology may explain these changes. Our results show that the same trends in eye movement characteristics of people with PD, as those observed by these authors, can be evoked by constraining head on body mobility in healthy participants. Therefore, it is possible that reduced head on body rotation due to increased axial rigidity is responsible for the eye movement behaviour observed in PD patients rather than pathologically altered oculomotor control.

In conclusion, the current study shows that experimentally constraining head on body rotation contributes to differences in eye movement, whole-body coordination and stepping behaviour during turning. Furthermore, turning slowly results in altered whole-body coordination and stepping behaviour. These results provide novel insights into normal turning behaviour than can be used to aid our understanding of turning dysfunction in pathological populations.

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Descriptive caption for each figure

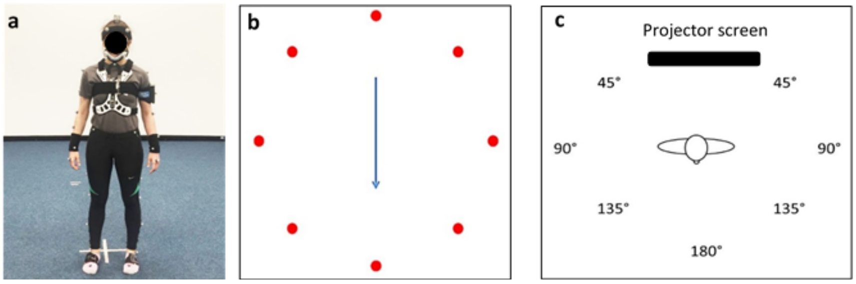


Figure 1. a) Participant wore a head, neck and chest brace, b) An animation on the video screen, c) Participants completing standing turns through 180 degrees either to the left or right.

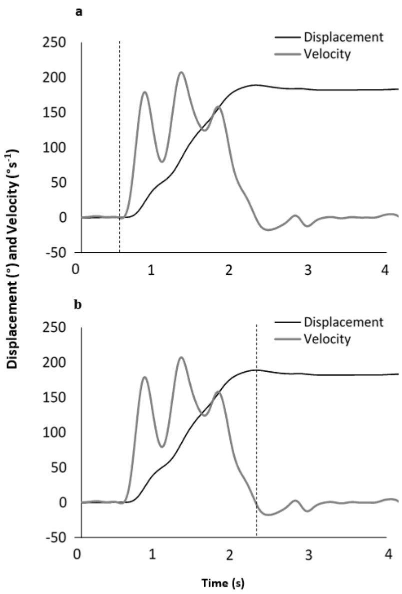


Figure 2. a) Indication of onset and offset using displacement (black line) and velocity (grey line) profiles.

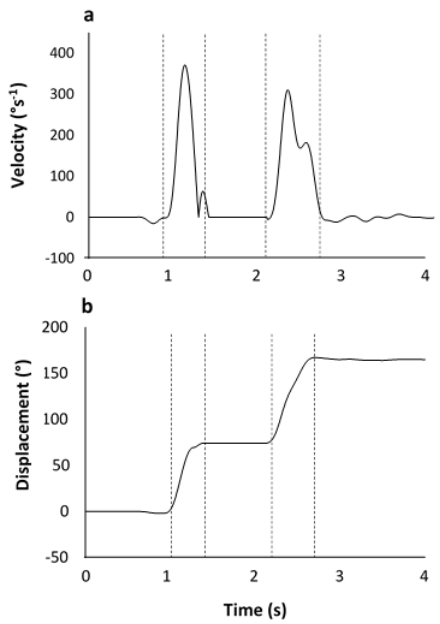


Figure 3. a) Step intervals velocity determination were shown by the dashed black lines to the left and right of each peak. b) Step onset and end time point determination (dashed line) that followed the peak velocity within each step interval.

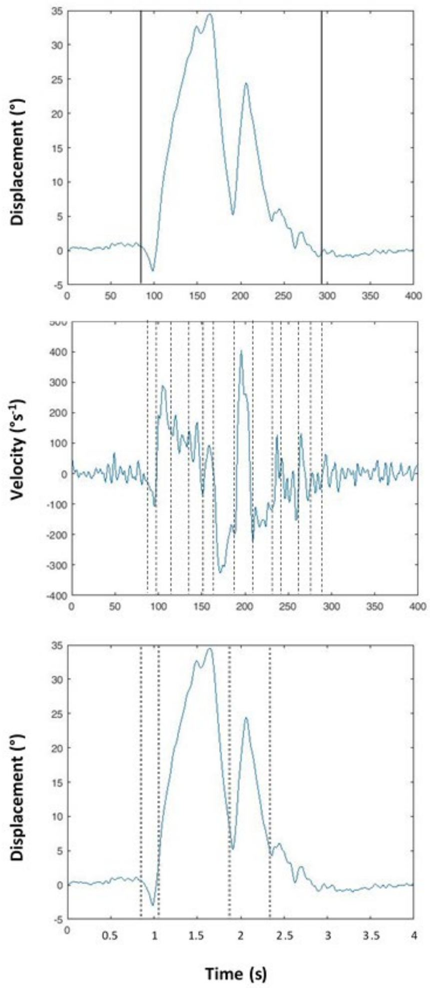


Figure 4. a) The nystagmus portion of the eye movement was selected to eliminate saccade/fixation combinations which were clearly outside the turn time based on the onset and end (black line of head rotation). b) Time intervals were determined from the zero crossings in the velocity profile (black dotted lines to the left and right of the peaks). c) Fast phases were included if peak velocity was ≥30°s-1and amplitude was ≥1.5°. Fast phase onsets were the positive zero crossings from the corresponding time interval (black dashed lines).

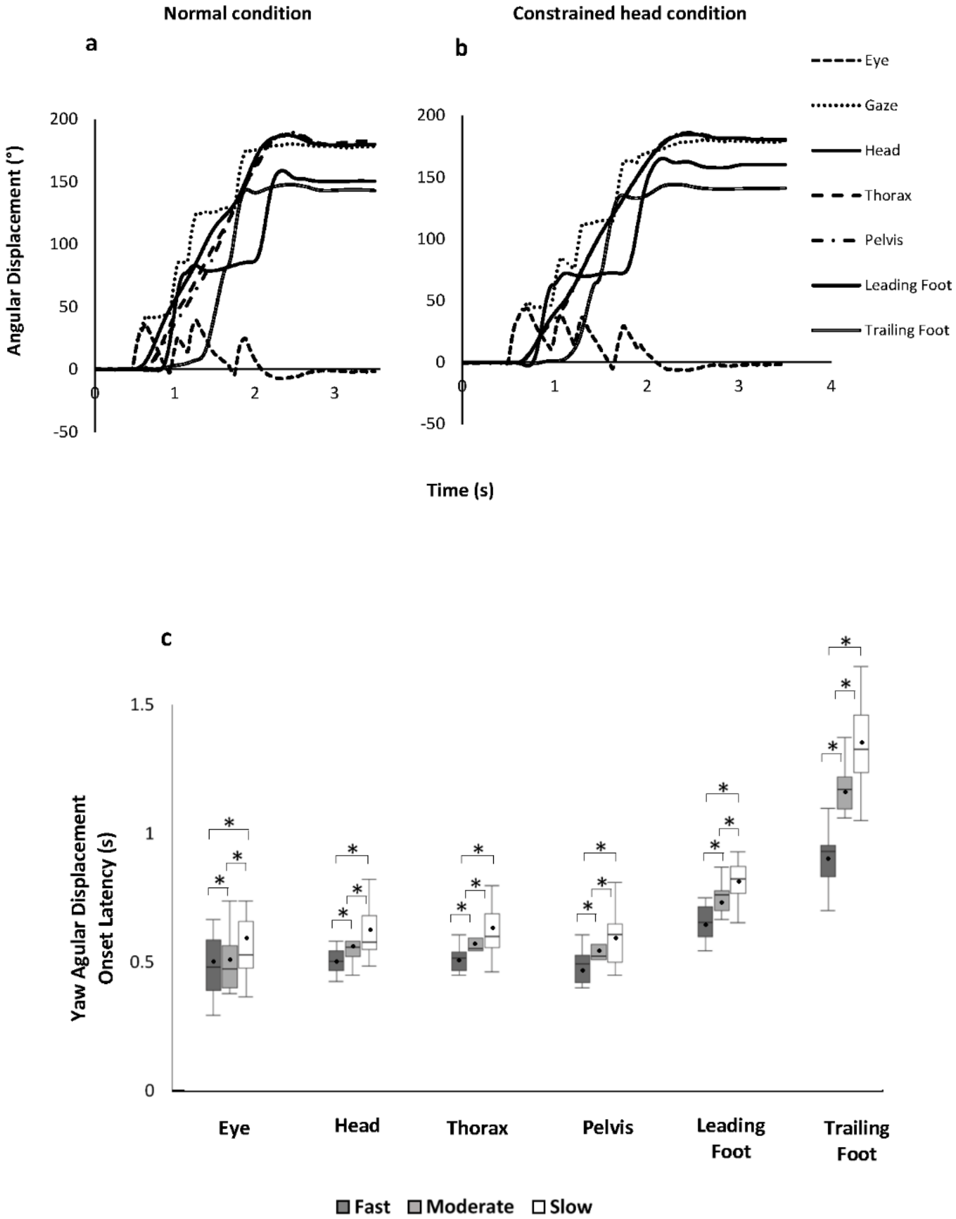


Figure 5. Turn displacement raw data from one trial at moderate speed for a, the normal condition, and b, the constrained head condition. Both traces clearly show that the gaze leads the other body segments throughout the majority of the 180° turn, reporting in the positive displacement. In both conditions normal condition, segment reorientation began with the eye, followed by the rotation of axial segments (head, trunk and pelvis) and, finally, the leading and trailing foot. c Boxplot showing the mean onset latencies with turning speed. There was a significant main effect of speed condition on the timing of rotation onset for all segments.

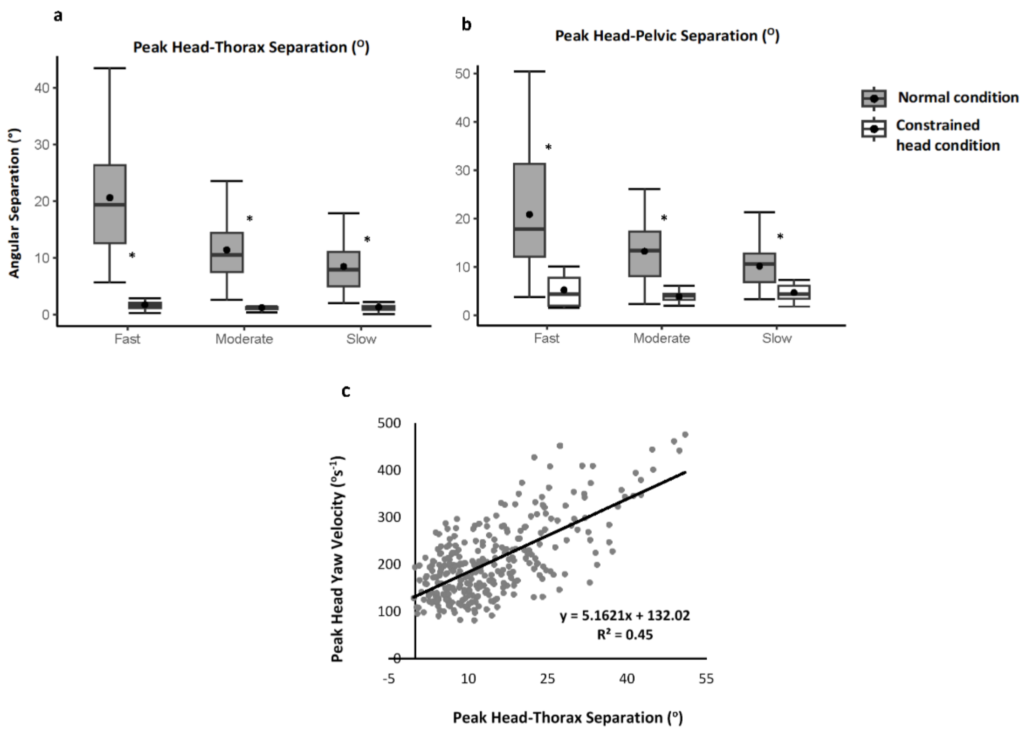


Figure 6. a The effects of turning speed on mean peak head–thorax angular separation and peak head–pelvis angular separation under both conditions. A box and whiskers plots diagram has been used to illustrate the median peak head–thorax angular separation and peak head–pelvic angular separation. b Scatterplot showing the results of regression analyses between peak head yaw velocity and maximum head-thorax angular separation during the normal condition, a significant positive correlation between peak head yaw velocity and the head-thorax separation was found ($R^2 = 0.45$, $P<0.005$) (* - significant main effect of turn condition).

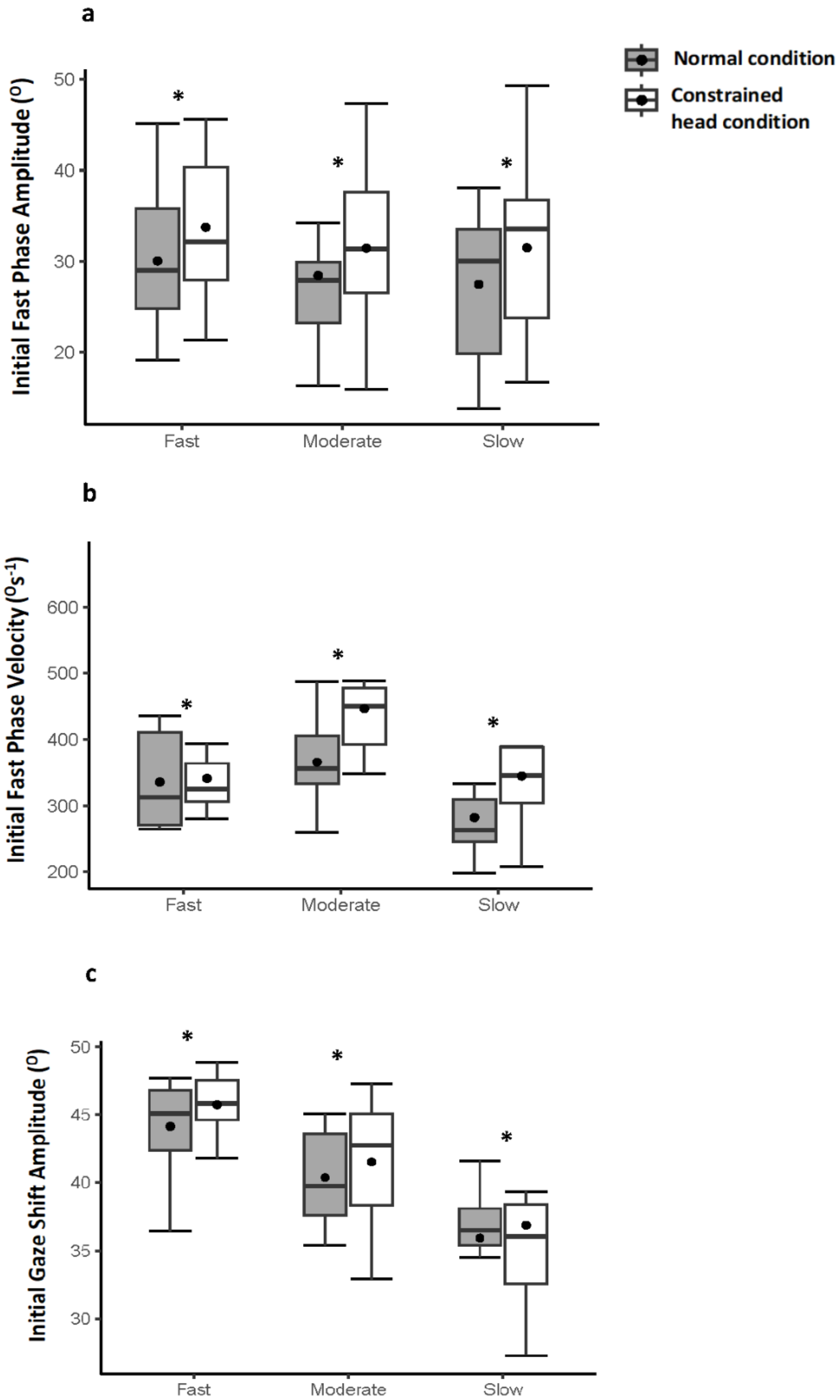
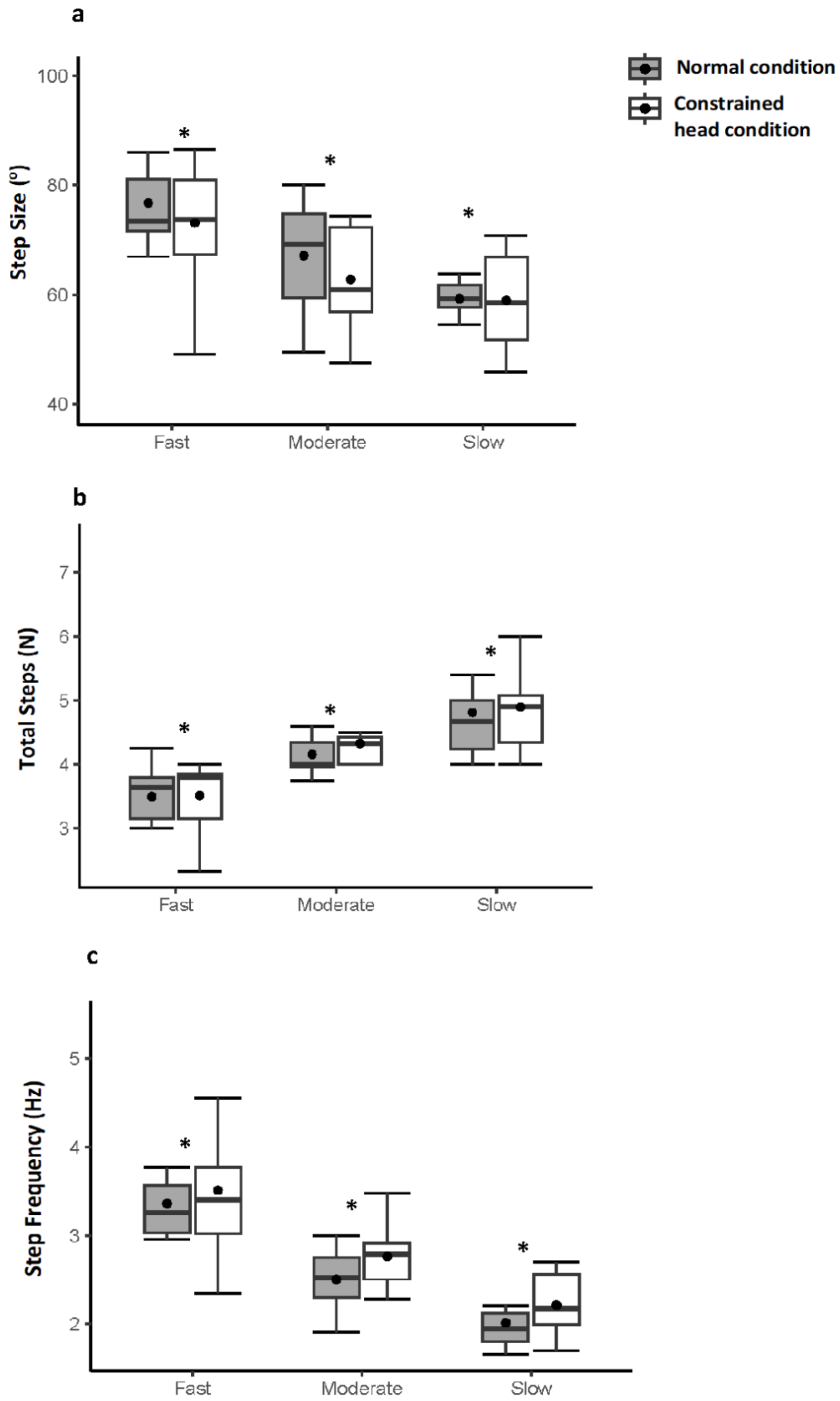


Figure 7. Experimentally inducing head and neck constraint had multiple effects on eye movement characteristics (* - significant main effect of turn condition).



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573 **Figure 8.** The effect of turn speed and turn condition on a. step size, b. the total number of

574 steps and c. step frequency taken to turn (* - significant main effect of turn condition).