SENSORY AND COGNITIVE INFLUENCES ON OCULOMOTOR AND WHOLE-BODY COORDINATION DURING STANDING TURNS

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Abstract

It is well-established that turning on the spot or changing the direction of walking involves a stereotyped sequence of eye, head and body segment rotation characterized by an anticipatory gaze strategy driven primarily by eye movements (nystagmus). However, the relationship between eye movements and whole-body coordination during turning has not been fully explored under different environmental and sensory contexts and as a result, the neural mechanisms responsible for this coordination are poorly understood. The first aim of this thesis was to investigate the effects of turn size and speed on eye movements and intersegmental coordination. Results showed systematic relationships between turn speed, amplitude and eye and whole-body coordination characteristics and that the timing of eye, head and axial segment reorientation onset does not accurately represent coordination during the turn. Secondly, we investigated the effects of either removing vision or suppressing eye movements during turns. We found that eye and motor behaviour during vision removal was similar to behaviour during full vision, however suppressing eye movements delayed gait initiation and decreased stepping frequency throughout the turn. Next we examined the influence of neck muscle vibration on turning and found that stimulating neck proprioceptors to evoke the CNS perception of head rotation with respect to the upper body resulted in early turn initiation. Lastly, we looked at the effects of divided attention using a secondary cognitive task during the turn. We found that turn onset was delayed during dual-tasking, but eye and body coordination were unaffected. We conclude that oculomotor nystagmus during turning represents a crucial component of an automatic, subcortically generated motor synergy, the release of which is dependent on cortical and sensory input (i.e. eye and neck proprioception). We propose that turning on-the-spot is organized centrally as part of a whole-body gaze shift rather than a specialized adaptation to conventional locomotion.

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Abbreviations

AP	Anterior-posterior
BG	Basal ganglia
BOS	Base of support
CNS	Central nervous system
COM	Centre of mass
COR	Cervico-ocular reflex
CPG	Central pattern generator
DBS	Deep brain stimulation
EOG	Electro-oculography
fMRI	Functional magnetic resonance imaging
FOE	Focus of expansion
FOG	Freezing of gait
FrACT	Freiburg Vision Test
FV	Full vision condition
FVCV	Full vision, contralateral vibration condition
FVIV	Full vision, ipsilateral vibration condition
GF	Gaze fixation condition
GVS	Galvanic vestibular stimulation
IRED	Infrared emitting diode
K-S Z	Kolmogorov Smirnov Z
LED	Light emitting diode
ML	Medio-lateral
MMSE	Mini Mental State Examination
MTT	Multiple Tasks Test
NFPF	Nystagmus fast phase frequency
NV	No vision condition
NVCV	No vision, contralateral vibration condition
NVIV	No vision, ipsilateral vibration condition
OKAN	Optokinetic after nystagmus
OKN	Optokinetic nystagmus
OKR	Optokinetic reflex
PD	Parkinson’s disease
PiG	Plug-in-gait

RM ANCOVA	Repeated measures analysis of covariance
RM ANOVA	Repeated measures analysis of variance
SCC	Semi-circular canals
SD	Standard deviation
SS	Serial subtraction
TO	Turn only
TUG	Timed Up and Go
VCR	Vestibulo-collic reflex
VE	Virtual environment
VOR	Vestibulo-ocular reflex
VR	Virtual reality
VSR	Vestibulo-spinal reflex

Chapter 1

General Introduction

Navigating through the world requires adaptive measures during locomotion such as steering around a corner or navigating around obstacles. Key information that allows us to make adaptations to our movement is mainly gained from three sensory sources: visual, vestibular and somatosensory. This sensory information is integrated within the central nervous system (CNS) to determine the body's current configuration, its position in relation to the environment and ultimately to control movement and motor coordination. Nearly every locomotor activity performed through the day involves some amount of turning. Steps taken during turns account for roughly 35-45% of all steps taken during a typical day (Glaister *et al.*, 2007). Turns are often cited as a difficult locomotor activity by older adults (Thigpen *et al*., 2000) and frequently leads to falls in patients with Parkinson's disease (PD) (Stack and Ashburn, 1999) and stroke (Hyndman, Ashburn and Stack, 2002). Falls during turns are more likely to occur sideways than during other motor activities (Cumming and Klineberg, 1994) and sideways falls result in hip fractures more often than forwards or backwards falls (Greenspan *et al.,* 1998). The ability to perform a turn is often used as a measure of mobility in physiotherapy. The Timed Up and Go (TUG) test, the gold standard test for functional mobility used by physiotherapists, requires patients to stand up from a seated position, walk 3 metres and make a 180° turn, then return to the chair and sit back down (Podsialdo and Richardson, 1991). The mobility problems experienced by fallers and neurological patients, particularly their turn performance has resulted in the current body of turning research being largely comprised of investigations into turning in PD patients, stroke patients and older adults. These studies have identified differences in oculomotor behaviour in PD (Lohnes and Earhart, 2011; 2012) and whole-body coordination in both PD (Crenna *et al.*, 2007) and stroke (Lamontagne, Paquette and Fung, 2007) which the authors have attributed to pathology, however, little is known about eye and whole-body coordination in young healthy individuals. Furthermore, many clinical studies have protocols which are incomparable as they incorporate either turns while walking, standing turns, or turn-like tasks which only require some turn behaviours, such as axial rotation (Degani *et al.*, 2010) or non-linear gait initiation (Vaugoyeau *et al.*, 2006; Vallabhajosula *et al.*, 2013). Some studies have implemented the TUG test within their experimental protocol (Thigpen *et al.*, 2000; Hollands *et al.*, 2010a; Herman *et al.*, 2014), however, most measure walking and turning to either one or multiple directions ranging from 30° to 90°. Very few studies have included a 180° condition which could be used for comparison with TUG test performance (Visser *et al.*, 2007; Spildooren *et al.*, 2010) and other studies with a 180° condition have included additional motor activities within the turn, such as picking up and carrying a tray (Nieuwboer *et al.*, 2009) or navigating around an obstacle (Willems *et al.*, 2007) or they have examined spontaneous 180° turns rather than controlled turns (Stack, Ashburn and Jupp, 2006). In addition to multi-directional turning, manipulations of gait speed have been incorporated into some clinical studies (Lamontagne and Fung, 2009; Akram, Frank and Chenouri, 2010; Akram, Frank and Fraser, 2010*)*, however, there are only a few studies on young healthy adults which have directly manipulated turn speed (Imai *et al.*, 2001; Vieilledent *et al.*, 2001; Xu, Carlton and Rosengren, 2004; Orendurff *et al.*, 2006), however, all of these studies have investigated changing speed during turns made while walking or altered gait speed during curved walking. Therefore more basic research is needed to fully understand how normal standing turns are coordinated, the sensory mechanisms used to control turns and the possible influences of cognition on motor behaviour in young healthy populations so that the results of studies with clinical populations or on ageing can be fully and correctly interpreted. The following section reviews the sensorimotor control aspects of the visual, vestibular and somatosensory systems, the interaction between attentional systems and eye movements and the current body of literature on the biomechanics and motor control of turning.

1.1 Vision

Of the sensory systems used for gait and posture, vision is the only one that can provide information about the environment from a distance (Patla, 1998) and appropriate visual sampling of the environment (e.g. safe places to step) is crucial for balance and safe walking (Hollands *et al.*, 1995).

The visual system is a complex sensory system which conveys information about environmental features and self-motion to the CNS and is intricately linked with the oculomotor system to achieve optimal function. Light is reflected off surfaces and enters the eye in rays which converge to form an image on the retina at the back of the eye. Convergence of light rays is achieved via the accommodative reflex which activates the ciliary muscles in order to change the shape of the lens to adjust focus (Fincham, 1951). At the back of the eye lies the retina which is a multi-cellular layered structure including the sensory receptors for vision, the photoreceptors. The fovea, the central region of the retina with the highest visual acuity, is densely packed with cones, photoreceptors which are stimulated in high levels of light. Throughout the periphery of the retina are rods, photoreceptors stimulated in low light levels which are necessary for night vision. In addition to photoreceptor density, visual acuity is dependent on the receptive field and the firing rate of retinal ganglion cells, which is largely determined by selective activation within the other cellular layers. When neighbouring photoreceptors are simultaneously activated, the arrangement of the receptive field determines whether the signal from the retinal ganglion will be excitatory or inhibitory.

Information from both retinas is sent via the optic nerves to the optic chiasm, where decussation occurs and the image of the left visual field from both eyes is sent to the left hemisphere and right visual field images are sent to the right hemisphere. Visual processing occurs in many regions of the brain, however, the majority of retinal ganglion axons are sent via the lateral geniculate nucleus to the visual cortex in the occipital lobe. From the visual cortex, vision is processed via two main pathways, the ventral and dorsal streams. The ventral stream runs along the temporal lobe and processes information related to object representation such as shape and colour while the dorsal stream, which runs along the parietal lobe, is largely involved with the processing of object location and movement (Milner and Goodale, 2008).

Around 10% of the retinal ganglion axons are sent to the superior colliculus in the midbrain, an important region which encodes for orienting movements of the eye and head (Sparks, 1999). The primary tasks of the oculomotor system are: 1) gaze stabilization, which maintains an image on the retina and 2) gaze shifting, which moves the fovea to an area of interest. Gaze shifting mechanisms are both voluntary and involuntary and include four main systems: saccades, which act to rapidly shift gaze; fixations, which act to maintain the eyes in a steady position via constant contraction of the extraocular muscles; smooth pursuit, which tracks the motion of an object; and vergence movements which move the eyes in opposite directions to either converge or diverge, depending on the distance of the object from the eye.

1.1.2 Visually-mediated gaze stabilisation

During head rotation, the visual image of the surroundings changes with respect to head orientation. In order to prevent the image slipping from the retina and maintain gaze stabilisation, counter-rotations of the eye are necessary; during sustained head rotation this produces a characteristic eye movement pattern called nystagmus which features alternating eye movements away from and back towards the central orbital position. Physiologically induced nystagmus (via either visual or vestibular input) has a saw-tooth appearance as the movements away from and back towards the orbit have different velocity profiles (Figure 1-1). Nystagmus induced by visual input is mediated by the optokinetic reflex (OKR) and is called optokinetic nystagmus (Masseck and Hoffman, 2009). Initially eye movement is in the direction of the moving visual stimulus and roughly matches the stimulus speed; this is called the slow phase of the movement. This is then followed by a quick movement back towards the central or primary position of the orbit, which is called the quick or fast phase of the movement. The slow phase of optokinetic nystagmus moves at a speed which keeps the visual image stationary on the retina; the OKR is effective at eliminating retinal slip at stimulus speeds up to 30°s^{-1}, less effective at higher speeds and completely ineffective above 100°s^{-1} (Brandt, Dichgans and Koenig, 1973). Gaze stabilization is also achieved via the vestibulo-ocular reflex (discussed in section 1.2.1) and the cervico-ocular reflex (discussed in section 1.3.1).

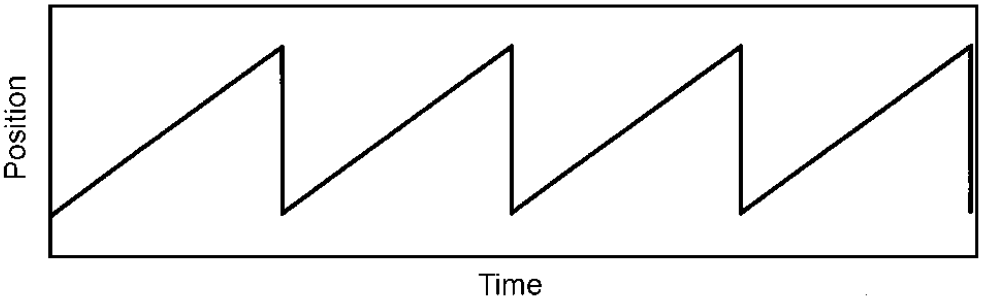

Figure 1-1: Reprinted from (Abadi, 2002). Schematic representation of physiologically induced nystagmus. The saw-tooth characteristic results from the differing velocity profiles of the slow and fast phases of the movement. During (visually induced) optokinetic nystagmus, the direction of the slow phase is away from the centre orbit as the slow phase movement functions to maintain the image of the visual stimulus on the retina and thus matches the stimulus' velocity. During vestibular nystagmus, the fast phase is away from the centre orbit (anti-compensatory) and the slow phase is back towards the centre orbit (compensatory). The slow phase velocity during vestibular nystagmus is mediated by the vestibulo-ocular reflex (see section 1.2.1) and approximately matches the velocity of head rotation.

1.1.3 Vision and gaze stabilisation during turns

During steering, gaze is alternately shifted and stabilised via fast saccade-like, anticipatory eye movements towards the turn direction and slow compensatory eye movements back towards the centre of the orbit (Figure 1-2). These anticipatory saccades are observed even when steering in darkness, despite the fact that no visual information is gained (Grasso *et al.*, 1998). Anticipatory eye movements appear to be necessary for coordinated steering; constraining eye movements via fixation causes significant disruptions in the timings of axial segment rotation, causing *en bloc* rotation both during visually evoked steering (Reed-Jones *et al.* 2009b) and during changes in gait direction (Ambati *et al.*, 2013).

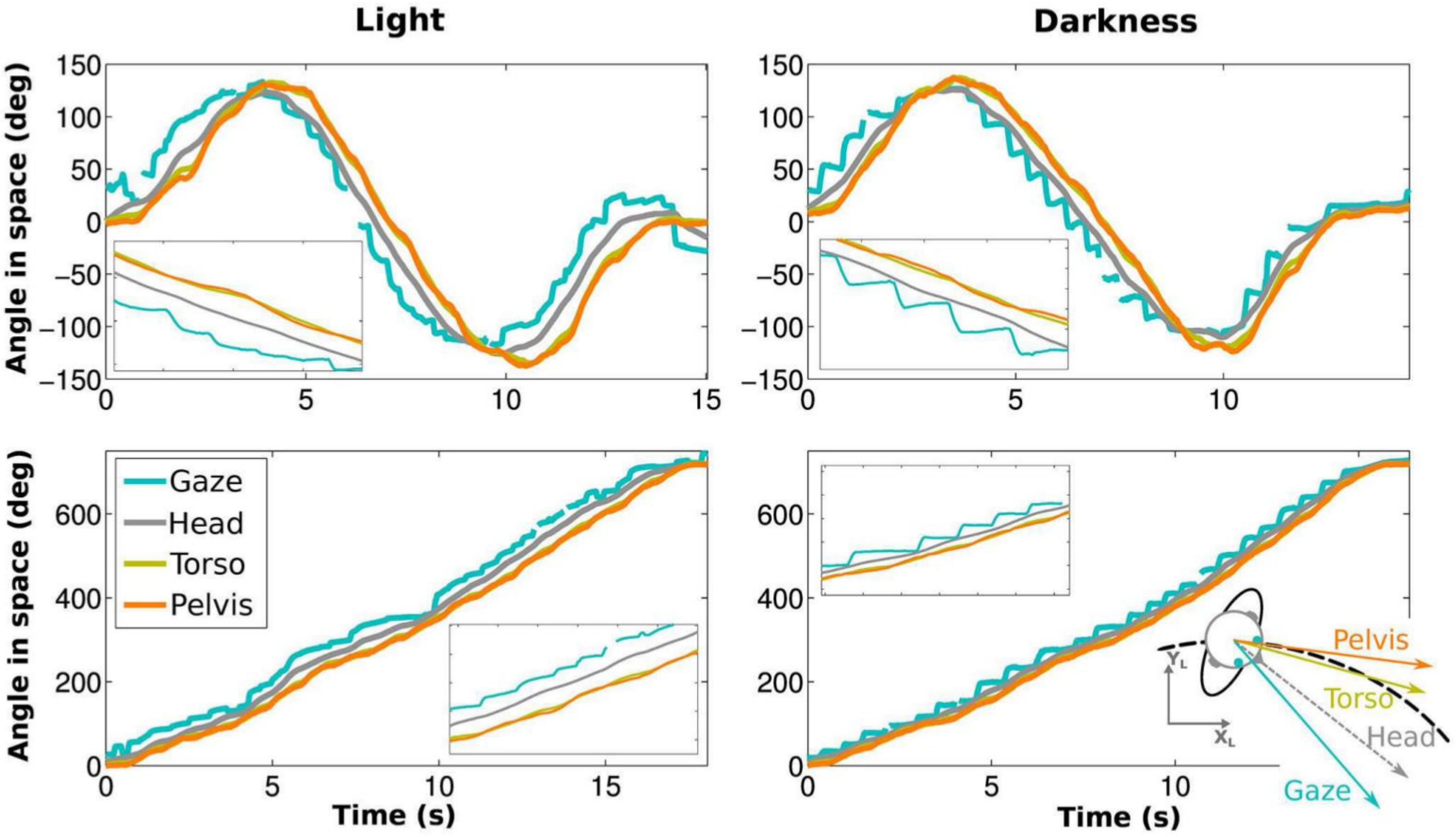

Figure 1-2: Reprinted from Authié *et al.*, 2015. Anticipatory eye movements towards the direction of movement occur during angular motion, both with and without visual input. Changes in heading direction are preceded by movements of the eyes.

In one of the first studies to examine turning in darkness, Grasso *et al.* (1998) had their participants perform right directed turns while walking around a 90° corner under both light and dark conditions. They hypothesized that if the anticipatory eye movements normally seen while turning were visually driven, then they would disappear in darkness, when visual input was unavailable. However, they found that anticipatory eye movements did indeed occur in darkness and that they systematically deviated towards the turn direction and anticipated future heading in a similar manner to eye movements observed in the light condition. They also tested the participants in a backwards turning condition where participants ‘reversed’ around the corner after completing the forwards turning task. This condition was to determine that if anticipatory eye movements are an integral part of the motor programme for curved locomotion, then they would be elicited during backwards curved walking. The authors predicted that if eye movements are hardwired in a specific pattern, then during backwards turning the eye displacement profile would resemble a time-reversed copy of eye displacement during forward turning. However, if eye movements were truly anticipatory, they would be directed towards the opposite direction, relative to the intended trajectory. Participants were found to have anticipatory eye movements (i.e. directed towards the left) during backwards turning, both in light and dark conditions. Differences in the eye movement characteristics were found between the different conditions, specifically the amplitude decreased when vision was removed and amplitude decreased more so during backwards turning. The time course of anticipatory movements was delayed in the backwards turning; the initial eye movement in forwards turning preceded movement around the corner by more than 1s while during backwards turning anticipation was delayed to less than 1s preceding movement around the corner. The study demonstrated that anticipatory eye movements are part of a gaze orientation synergy that is an integral part of nonlinear locomotion.

Courtine and Schieppati (2003a) investigated whole-body kinematics during curved locomotion in both eye-open and eyes-closed conditions. They found that with vision, participants were able to successfully complete the required path without difficulty, but removal of vision increased path deviations and variability. Progression velocity significantly decreased during curved locomotion without vision, however, they also compared curved walking with straight walking which showed that reductions in walking velocity were comparable to reductions in turning velocity. Additionally, they examined foot position during each step and found no significant differences in stepping behaviour between vision conditions. Investigations into circular walking (Takei *et al.*, 1997) and complex trajectory walking (Authié *et al.*, 2015) have found similar results; participants are able to successfully navigate curvatures without vision, however path deviations and trajectory variability increase when vision is removed.

Segmental coordination during standing turns in older adults has been investigated during eyes-open and eyes-closed conditions (Akram, Frank and Fraser, 2010). In the eyes-open condition, older adults reoriented their head, shoulders and pelvis simultaneously or in an *en bloc* manner. With eyes-closed, the segment onset latencies were delayed and even more synchronous than with vision. The investigators examined the intersegmental coordination between the head and shoulders and the head and pelvis. They found that during eyes-open the head separates from the shoulder and pelvis, while *en bloc* rotation continues throughout the turn with eyes-closed. While they found that the velocities of all segments significantly decreased with eyes-closed, the timing of the peak velocities with respect to the turn duration did not differ significantly between conditions. The authors reasoned that the demonstrable differences in head movement between conditions were likely due to the role of the head in coordinated eye-head movements during visual sampling of the environment, a function which is negated when vision is removed.

Lamontagne *et al.* (2010) directly manipulated visual input during steering by examining participants in an immersive virtual environment (VE). They altered the direction of optic flow, or the pattern of visual motion across the retina during self-motion by placing a focus of expansion (FOE) located in one of five possible locations in their field of view (0°, ±20°, ±40°). The participants were given two different tasks: maintain a straight heading in the physical world or maintain heading within the VE. Participants were able to successfully maintain heading within the VE, however, within the physical environment, heading deviated in the direction opposite the FOE location and deviation amplitudes were scaled to the magnitude of the FOE (i.e. larger deviations in 40° than 20°). In addition to altering heading direction and trajectory, the illusion of self-motion in a VE has been shown to elicit steering-like segmental coordination (Reed-Jones *et al.*, 2009a). While stepping-in-place, participants viewed a virtual scene of movement down a corridor and around a corner. Just preceding the corner, participants made fast eye movements in the direction of the virtual turn, which was followed by rotation of the head and trunk in a sequential manner. Researchers found that timing of the eye movements and axial rotation resembled the same sequenced order and had the same temporal characteristics of reorientation during actual turns.

1.1.4 Summary

The removal of vision during turning causes slowed movements and alters axial segment rotation in older adults, but does not appear to affect stepping behaviour during curved walking. The stereotyped eye movements which occur during turning are present both with and without visual input and occur in a predictive or anticipatory manner whereby they are directed towards the direction of the turn preceding the movement of the head. Constraining these anticipatory eye movements causes disruptions in axial segment coordination at turn initiation. The following section will review the physiology and gaze stabilising mechanisms of the vestibular system as well as the vestibular contribution to spatial orientation perception.

1.2 Vestibular system

Located within the inner ears, the vestibular system functions to detect positional changes of the head and contributes to spatial orientation (Day and Fitzpatrick, 2005) via projections sent to the oculomotor nuclei as well as to descending spinal tracts. The vestibular labyrinth is divided into two parts: the semi-circular canals (SCCs) and the otolith organs. The three SCCs which are positioned orthogonally are the lateral/horizontal SCCs, the superior/anterior SCCs and the posterior SCCs which respond to angular accelerations of the head around the yaw, pitch and roll axes, respectively. Linear acceleration is detected by the otolith organs: the saccule and utricle, which respectively respond to vertical and horizontal translations. The two labyrinths are reciprocally innervated, so that movements in one direction will cause an excitatory signal (depolarisation) in one ear and an inhibitory signal (hyperpolarisation) in the other; the integration of these afferent signals can accurately estimate the orientation and movement of the head on the body.

There are two main descending tracts from the vestibular nucleus, starting in the medial vestibular nucleus and lateral vestibular nucleus. The lateral vestibulo-spinal tract descends from the lateral vestibular nucleus ipsilaterally through the spinal cord to the sacral level, synapsing on lower motor neurons serving the trunk and lower limb, which mediate vestibulo-spinal reflexes (VSR), or ‘righting reflexes’ (Rutka, 2004). VSRs cause paired agonist-antagonist activity in anti-gravity muscles to maintain an upright posture. The medial vestibulo-spinal tract descends bilaterally from the medial vestibular nucleus to the mid-thoracic/cervical level of the spinal cord, synapsing on motor neurons serving muscles of the neck. The vestibulo-collic reflex (VCR) is limited to the musculature of the neck and serves specifically to stabilise the head-on-trunk position. Welgampola and Colebatch (2001) confirmed that the VSR and VCR are mediated via different pathways as the VSR showed attenuation to different postural and visual conditions under galvanic vestibular stimulation, while the VCR remained constant throughout each condition.

1.2.1 Vestibular-mediated gaze stabilization

In addition to head and trunk stabilising responses, the vestibular system also contributes to one of most important gaze stabilising mechanisms, the vestibulo-ocular reflex (VOR), which arises through an ascending pathway (via the medial longitudinal fasciculus from the medial vestibular nucleus and superior vestibular nucleus to the oculomotor nucleus, trochlear nucleus and abducens nucleus which collectively control the extra-ocular muscles (Rutka, 2004). The VOR compensates for both rotational and translational head movement by generating very short latency (~15ms) eye movements in the direction opposite head motion to stabilise the fovea in a central orbital position. Stabilisation of the fovea is necessary, as this is the area of the retina with the highest visual acuity and gaze stabilisation provides a clear visual image by preventing retinal slip. Importance of VOR function is underlined by the increased gain of the cervico-ocular reflex when the vestibular system is compromised (Jürgens, Mergner and Schmid-Burgk, 1982).

Vestibular nystagmus is elicited during sustained head rotation and has a saw-tooth pattern similar to optokinetic nystagmus (Figure 1-1), however, the direction of the slow phase and fast phases of vestibular nystagmus differ from optokinetic nystagmus. During vestibular nystagmus, the fast phase is directed away from the centre orbit and the slow phase is the eye movement back towards the centre orbit. The velocity of the slow phase of vestibular nystagmus roughly matches the velocity of head rotation as it is driven by the VOR.

1.2.2 The vestibular system during whole-body rotations

Isolating vestibular input during active whole-body rotations is difficult as active rotation of the head elicits an appreciable amount of proprioceptive input. Therefore, many studies investigating vestibular input compare passive and active rotations. Zanelli and colleagues (2011) investigated spatial perception in young healthy adults. They had participants stand blindfolded on a rotating platform, which moved clockwise and anti-clockwise to 45°, 90°, 135°, 180° and 360° at one of three angular velocity profiles with a constant duration of 4s or at a controlled peak velocity ($57°s^{-1}$) with five different durations. At the end of the stimulus, the participant gave a verbal estimation of the imposed rotation amplitude followed by an active rotation back to their starting position. Participants consistently overestimated the imposed rotation amplitude, but were generally able to reproduce their own estimations accurately e.g. a participant estimates a 90° imposed rotation, when the actual stimulus was 45°, but accurately reorients himself to 90°. A slight discrepancy occurred during 360° trials, as participants were able to accurately estimate, but not able to reproduce a 360° turn. The authors concluded that their results demonstrated the necessity of active motion for accurate interpretation of spatial orientation and emphasized the role vision plays in correcting positional errors.

During turning, the VOR is used to generate the slow phases of nystagmus, which return the eyes to a neutral orbital position between intermittent fast eye movements towards the turn direction. Panichi *et al.* (2011) measured eye movements during passive whole-body rotations with either passive or active head stabilisation. Participants stood on a rotating platform with their pelvis and shoulders fixed-in-place. During passive trials, the head was also fixed-in-place and during active trials, the participants were required to maintain the given head position. Participant's heads were positioned facing either straight ahead or 45° to the left or the right while the platform oscillated either symmetrically or asymmetrically. The deviated head positions affected the slow phases of the eye movements as their amplitude increased during both symmetrical and asymmetrical oscillations, but these effects only occurred during active head stabilisation. The authors concluded that active head stabilisation improves gaze stability.

1.2.3 Summary

The vestibular system responds to movements of the head during both angular and translational movement and contributes to the perception of spatial orientation. An important function of the vestibular system is to generate the compensatory eye movements of the VOR which stabilise gaze on the retina during head motion. The slow eye movements during turning are generated by the VOR to stabilise gaze during prolonged head rotation. The following section will review the physiology and gaze stabilising mechanisms of the somatosensory system, as well as experimental manipulations of proprioception during posture.

1.3 Somatosensory system

Somatosensation can be divided into two distinct parts: proprioception and cutaneous sensation, generally referred to as touch. The sensory receptors for somatosensation are located throughout the body, embedded in the epithelium, muscles, tendons and joints; the afferent signals collectively inform the CNS of the relationship of the body to the environment as well as the relationships between the body segments.

Embedded within cutaneous tissue are mechanoreceptors which selectively respond to different types of tactile stimulation and have different speeds of adaptation which lead to an array of tactile experiences. Merkel cells have slow adapting properties and respond to sustained compression of the skin, which allows for high spatial resolution and sensitivity to textures (Johnson, 2001). Meissner corpuscles are rapidly adapting and are sensitive to rapid skin deformation, such as vibration. Pacinian corpuscles are another rapidly adapting mechanoreceptor, which respond to high frequency vibrations (Mountcastle, 2005). Ruffini endings are slowly adapting receptors which respond to slow sustained skin deformation, including stretch or tension. Lastly, are fast adapting hair follicle receptors respond to hair movement, but not sustained deflection of the hair.

Sensory receptors for proprioception include the muscle spindle and Golgi tendon organ which are respectively located in the muscle belly and muscle-tendon junction. Muscle spindles consist of nuclear bag and nuclear chain fibres, which lie in parallel, and have primary and secondary afferents located centrally and eccentrically, respectively, along the fibre (Mileusnic *et al.*, 2006). During muscular contraction, the spindles experience a change in length comparable to the change in muscle length and information about the change in length as well as the velocity of the change in length are sent via primary and secondary afferents. Efferent signals are also sent to the muscle spindles to contract the intrafusal fibre, which adjusts the sensitivity of the spindle, so that its signals are effective over a wide range of lengths and velocities. Golgi tendon organs, which are attached to the extrafusal fibres at one end and a tendon at the other, are responsive to changes in force (Mileusnic and Loeb, 2006). Golgi tendon organs almost exclusively respond to forces developing within the muscle; forces applied to passive muscle require approximately 100,000 times greater force to cause depolarisation (Al-Falahe, Nagaoka and Vallbo, 1990). Additionally, there are receptors in the joints that are structurally and functionally similar to cutaneous receptors and respond to deformation and stretch of the joint tissue (Proske and Gandevia, 2009).

1.3.1 Proprioception-mediated gaze stabilization

The proprioceptors of the neck and cervical joints interact with the oculomotor nuclei to elicit a gaze stabilising mechanism similar to the VOR, called the cervico-ocular reflex (COR). However, the COR is difficult to elicit experimentally in normal healthy individuals (Sawyer *et al.*, 1994); conflicting reports tell that in response to a visual stimulus COR gain increases (Huygen, Verhagen and Nicolasen, 1991) or COR gain decreases (Barlow and Freedman, 1981), and that the presentation of cervical nystagmus in healthy individuals differs from those seen in labyrinthine-defective patients who generally exhibit higher COR gain than healthy individuals (Huygen, Verhagen and Nicolasen, 1991). Overall, the COR appears to be under-utilised as a gaze-stabilising mechanism until the sensory signals contributing to the OKR and VOR are compromised, following which the COR gain is up-regulated as seen in labyrinthine defective patients (Bronstein and Hood, 1986; Huygen, Verhagen and Nicolasen, 1991) and adults over the age of 60 (Kelders *et al.*, 2003).

1.3.2 Manipulating somatosensation

Lower limb cutaneous sensation and proprioception are frequently examined during postural and locomotor tasks, not surprisingly as knowledge of terrain is essential for corrective adaptations to motion. During unperturbed stance, forefoot and whole-foot sole anaesthesia increase sway in the medio-lateral and anterior-posterior directions, respectively in comparison with full plantar sensation (Meyer, Oddsson and De Luca, 2004). This effect is exacerbated when vision is removed. Translational perturbations during foot-sole cooling cause different stepping strategies to be adopted which decrease the duration of single leg support versus control conditions where wide steps were used to increase the base of support (Perry, McIlroy and Maki, 2000). Additionally, the authors found direction specific responses to each perturbation and concluded that plantar cutaneous receptors may contribute to the internal representation of the postural limits of stability. Sorensen *et al.* (2002) found similar results using stance leg muscle vibration during obstacle crossing which showed that centre of mass (COM) displacement, acceleration and the location of the COM in relation to the centre of pressure altered significantly when muscle spindle afferents were manipulated. Proprioceptive deficits higher in the limb (i.e. knee) have been shown to cause a delay in the onset of steering reorientation, suggesting that proprioceptive feedback prior to movement initiation is required for adapting locomotion (Reed-Jones and Vallis, 2007).

Manipulation of neck muscle proprioception via vibration has been shown to have significant effects on gait and posture and these effects vary with the site of stimulation. Continuous lateral neck vibration causes increased lateral sway during quiet stance as well as head turning with accompanied body deviation away from the site of stimulation (Smentanin, Popov and Shlykov, 1993). Asymmetrical lateral neck vibration causes significant body deviations during walking and to a lesser extent during running (Courtine *et al.*, 2003) and sustained rotation away from the stimulus during stepping-in-place (Bove, Courtine and Schieppati, 2002). Dorsal neck muscle vibration during quiet stance causes sway in the direction of the naso-occipital axis when the eyes are in primary position and sway follows gaze when the eyes are deviated (Ivanenko, Grasso and Lacquaniti, 1999). Gaze-directed deviations are also seen during stepping-in place, which is accompanied by involuntary forward motion (Ivanenko, Grasso and Lacquaniti, 2000). Additionally, sustained dorsal neck vibration causes changes in walking speed; vibration increases forward walking speed and decreases backward walking speed. Neck muscle vibration can also induce eye movements, which like motion, is dependent on the site of vibration (Lennerstrand, Han and Velay, 1996; Han and Lennerstrand, 1999). Collectively, these studies suggest a prominent interplay between the processing of somatosensory and visual signals.

1.3.3 Summary

Somatosensory signals arise throughout the body from both cutaneous and proprioceptive receptors. Integrated somatosensory signals in the CNS indicate the positional relationships between different body segments which is used to inform motor control during motion. Manipulating neck proprioception via vibration signals head-on-trunk rotation in the CNS and can elicit turning-like behaviour during stepping-in-place. Currently there are no published studies which directly manipulated or perturbed proprioception during active whole-body turns. The next section moves from discussing the sensory systems to addressing the role of cognition on gait and posture.

1.4 Cognitive influences on oculomotor and motor behaviour

In addition to the clear effects of altered sensory feedback, there is increasing evidence that there is an influence of attention on gait and posture control. Attention is a multi-faceted aspect of executive function which relates to how stimuli in the environment are perceived and then subsequently processed in the central nervous system (Lezak, 1995). Attention is divided into separate categories which include: selective attention, sustained attention, divided attention and alternating attention (Rogers, 2006). To test the effects of attention of gait and posture, normally dual-tasking protocols are used which divide attention, or the ability to perform more than one task at the same time. The null hypothesis during dual-task paradigms is that gait is automatic and does not require attention, thus simultaneously performing another task during gait will affect neither gait nor the performance of the secondary task.

While simple cognitive tasks, such as responding to an auditory or visual stimulus, appear to have no effect on gait performance (Lajoie *et al.*, 1993; 1996; Abernethy, Hanna and Plooy, 2002; Sparrow *et al.*, 2002) there is substantial evidence that divided attention caused by dual-tasking during gait in young healthy adults disrupts gait performance and that the effect is compounded by the level of demand of the secondary task (Yogev, Hausdorff and Giladi, 2008). General findings in dual-task research show that younger adults slowed gait speed, altered temporal gait characteristics (i.e. increased time spent in double support; decreased stride length; increased cadence) and incurred collisions during obstacle avoidance (Ebersbach *et al.*, 1995; Weerdesteyn *et al.*, 2003; Shkuratova *et al.*, 2004; Grabiner and Troy, 2005).

The simultaneous performance of two separate attention-demanding tasks causes competition for attentional processing in the brain, and additionally requires prioritisation of the two tasks. Bloem *et al.* (2001) set out to test which task, the motor or the cognitive task, was prioritised during a series of functional tasks of increasing difficulty, including obstacle avoidance and holding a tray while walking, and compared young healthy adults with older healthy adults. They found that when the complexity of the task increased, the motor task was prioritised over the cognitive task by the younger adults and by most of the older adults, which they coined the ‘posture first’ strategy. In contrast, a follow-up study found that PD patients, who have separate motor and executive function deficits, use a ‘posture second’ strategy which unnecessarily increases their risk of falling when dual-tasking (Bloem *et al.*, 2006).

While it appears that age-related changes in gait during dual tasking is limited by the subtle age-related decline in executive function (Yogev, Hausdorff and Giladi, 2008), poor visual attention in older adults is significantly related to poor mobility (Owsley and McGwin, 2004). Visuospatial attention and eye movements are intricately linked as there are common networks in the brain which process both attention and eye movements (Hoffman and Subramaniam, 1995; Corbetta *et al.*, 1998). These findings suggest that divided attention could lead to inappropriate visuomotor behaviours which may directly lead to impaired gait and posture. Inappropriate shifts of visual attention were demonstrated by Chapman and Hollands (2007) during visually guided stepping which directly lead to stepping errors, however, oculomotor behaviour is rarely, if ever, measured during dual-tasking paradigms, which only allows for speculation on how eye movements might relate to motor performance.

1.4.1 Dual-tasking while turning

There is currently little information about the effect of performing a secondary cognitive task on turning performance. Hollands *et al*. (2014) investigated changes in the stepping behaviour of stroke survivors and healthy age-matched controls during walking turns to 90° while concurrently performing a serial subtraction task. They found that performance of the secondary task resulted in both groups taking more time to turn, and demonstrating increased stepping variability and increased single support time on the inside leg of the turn. Gait characteristics were measured in PD patients making 180° and 360° turns while concurrently performing a verbal cognitive task (Spildooren *et al*., 2010). They found that addition of the secondary task increased the performance differences between PD patients who were 'freezers', who frequently had freezing of gait (FOG) episodes and non-freezers. Additionally, FOG episodes were triggered more often during dual-tasking than during turning alone. Currently there are no studies which have investigated the effect of dual-tasking on turning in young healthy adults.

1.4.2 Summary

There is increasing evidence that attention plays a role in the motor control of gait and posture. The complexity of the secondary cognitive task during dual-tasking appears to determine whether there will be an effect of divided attention on gait. Effects of divided attention on movement usually results in delayed reaction times, presumably due to the increased processing time required to initiate movement. There is currently little knowledge on the effects of dual-tasking on turning, but it does appear to affect stepping characteristics in older adults and stroke patients and increases the frequency of FOG episodes in PD patients. The following section moves from discussing cognition to describing how motor and oculomotor behaviour is coordinated during turning.

1.5 Coordination of turning

1.5.1 *Segment reorientation*

A clear reorientation of each body segment has been demonstrated in both on-the-spot and locomotor turns (Figure 1-3) which shows steering is usually initiated with a saccade towards the turn direction, followed by rotation of the head, then the trunk and pelvis and finally the stepping movements of the feet (Hollands, Sorensen and Patla, 2001; Imai *et al.*, 2001; Hollands, Patla and Vickers, 2002; Hollands, Ziavra and Bronstein, 2004; Reed-Jones *et al.* 2009a; 2009b, Anastasopoulos *et al.*, 2009). Older adults use the same temporal sequence as younger adults, however, spatial characteristics differ slightly (Fuller, Adkin and Vallis, 2007; Paquette *et al.*, 2008; Baird and Van Emmerik, 2009); young adults generally achieve a greater amount of head-on-trunk rotation than older adults. Older adults and neurological patients have been shown to initiate turns *en bloc*, whereby all the axial segments rotate at approximately the same time (Crenna *et al.*, 2007; Lamontagne, Paquette and Fung, 2007; Huxham *et al.*, 2008; Lamontagne, Perlmutter and Earhart, 2009; Akram, Frank and Fraser, 2010; Wright *et al.*, 2012), however, many studies have also found the typical sequential reorientation in these populations (Hollands *et al.*, 2010a; 2010b; Anastasopoulos *et al.*, 2011; Mari *et al.*, 2012; Anastasopoulos *et al.*, 2013; Ahmad *et al.*, 2014). Unfortunately, measurements of *en bloc* turning are usually limited to comparisons between segment onset latencies and whether the axial segments continue rotating together throughout the turn is not determined.

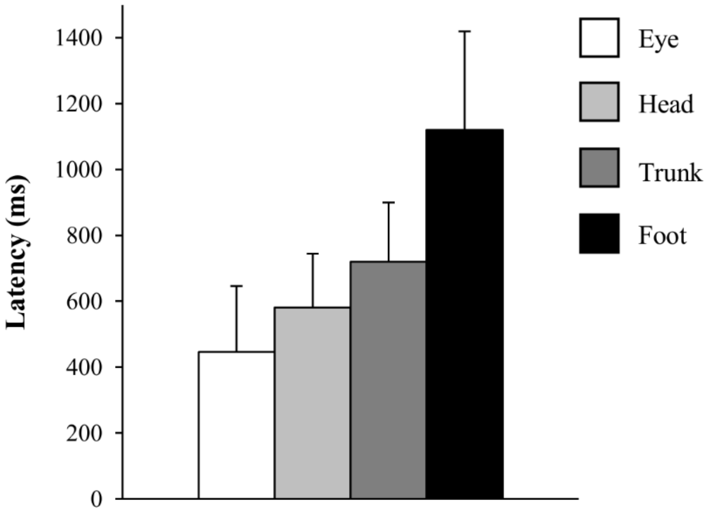

Figure 1-3: Recreated from (Anastasopoulos *et al.*, 2009). Segment onset latencies are typically measured in order to determine the sequence of reorientation during turning.

1.5.2 *Anticipatory saccades and nystagmus*

Before changing direction, whether during walking (Grasso *et al.,* 1998; Hollands, Patla and Vickers, 2002), steering a motor vehicle (Land and Lee, 1994; Wilkie and Wann, 2003; Wilson *et al.,* 2007) or on-the-spot turns (Hollands, Ziavra and Bronstein, 2004; Anastasopoulos *et al.,* 2009), humans normally align their gaze with a desired movement direction. These anticipatory eye and head rotations, which presumably serve to provide a reference frame for guiding subsequent body or alignment in space, are seen in complete darkness and even during backwards walking (Grasso *et al.,* 1998). Evidence suggests that the visual information gained from anticipatory eye movements may contribute to the reorientation of the body. A study standing turns towards either visually-cued locations (indicated by a lit LED in a circular array of eight LEDs spaced 45° apart; see Figure 1-4) or memory driven locations found that during memory driven trials, where participants returned to the starting position following the visually-cued trials, participants used the same initiating eye movements as during the visually-cued turns, however axial segment reorientation was more simultaneous than the visually-cued trials, with the head and trunk sometimes preceding eye movement (Anastasopoulos *et al.*, 2009). However, a study by Ashburn and colleagues (2014) using a targeted paradigm which was limited to 180° turns found that the initial eye movement during on-the-spot turns usually *followed* head movement.

During large slow gaze shifts, such as those that occur during large body rotations to locations outside of the oculomotor range, individuals rarely generate single step gaze shifts, Instead, gaze reorientation is accomplished, after the initial coordinated gaze shift, with the contribution of vestibular nystagmus until the new target is fixated (Grasso *et al.*, 1998; Anastasopoulos *et al*., 2009). Nystagmus is characterized by a series of alternating quick phase saccadic eye movements in the direction of the turn interspersed with slow phase drifts back towards central orbit compensating for on-going head rotation (Figure 1-4). Sklavos and co-workers (2010) found that the contribution of the nystagmus directly correlated with the amplitude of the turn. Additionally eye pitch movements occur opposite head movement direction and eye roll movements occur in the same direction as the head to maintain a steady eye-in-orbit position (Imai *et al.*, 2001).

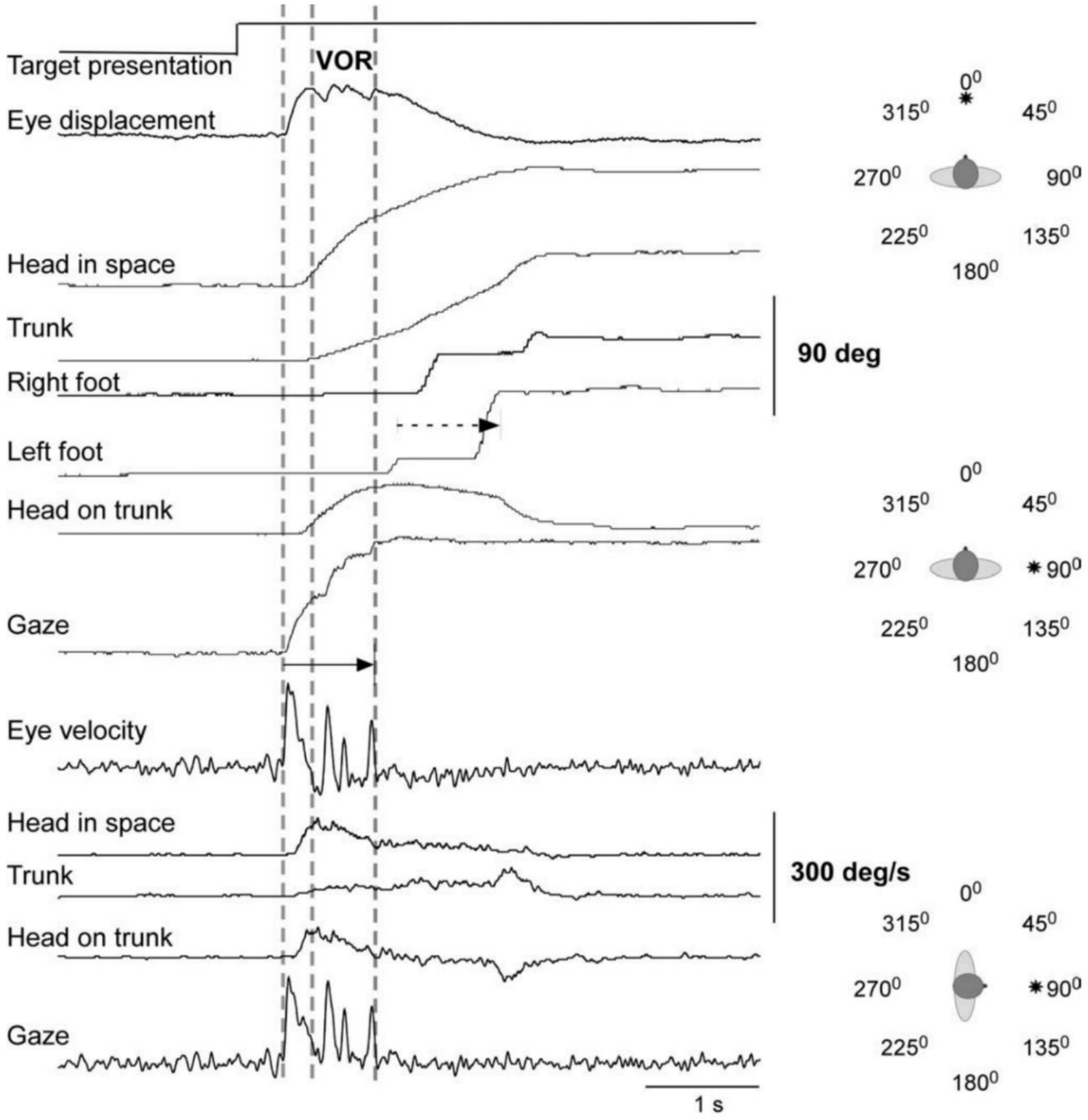

Figure 1-4: Reprinted from Anastasopoulos *et al.*, 2011. An example of raw eye and kinematic data from a 90° turn which clearly demonstrates an initiating eye movement prior to head movement followed by nystagmus. The steep slope of the eye displacement curve in the positive direction represents the fast phase of nystagmus while the more gradual descending slope after the peak represents the slow phase of nystagmus, generated by the VOR.

A subsequent study by Anastasopoulos *et al.* (2015) found that nystagmus characteristics during very fast turns differed significantly from those seen at a natural speed (Hollands, Ziavra and Bronstein, 2004; Sklavos, Anastasopoulos and Bronstein, 2010). During natural, slower turns, single-step gaze shifts to eccentric targets only occurred in around 30% of trials, but this dramatically increased in fast turns to 70% of trials. Examination of kinematic data showed that head velocity was significantly higher during single-step gaze shift trials than multi-step gaze transfers. However, they found that eye-in-orbit characteristics did not differ between single- and multi-step transfers and therefore it was proposed that head-in-space and eye-in-orbit movements may be controlled by separate mechanisms.

1.5.3 *Head anticipation*

Anticipatory head movements aid in attaining a stable frame of reference from which appropriate sensory information can be utilised. Head yaw typically leads trunk yaw by approximately 25° of rotation (Imai *et al.*, 2001). A study of curved locomotion also showed the presence of anticipatory head movements of approximately 220 ± 90ms ahead of trunk movement (Courtine and Schieppati, 2003a); they also found that the head was progressively turned towards the centre of the circle as motion progressed.

Several studies have subjected the head to various conditions to test the robustness of head anticipation, Hollands and co-workers (2001) demonstrated that, if the head is immobilised with respect to the shoulders while walking and changing directions, the trunk reorients earlier than during normal head free turns. This strategy is presumably used to maintain the anticipatory nature of the head. External perturbations to the head during turning also affect subsequent segment reorientation; using a device fitted to the head to move it in the yaw direction, Vallis and colleagues (2001) found that when unexpected head perturbations occurred toward the direction of the turn one step prior to the turn, sequential segment orientation was preserved. However, when the head was perturbed in the direction opposite the turn, the onset latency of each segment was delayed until the head was oriented towards the travel path and body segments rotated *en bloc*. Further exploration by the same research group found that sequential segment reorientation or the ‘steering synergy’ can be released automatically following an unexpected head perturbation in the yaw direction (Vallis and Patla, 2004). They found that a subset of this synergy (trunk yaw and centre of mass translation in the medio-lateral plane) is released following voluntary head movements in the yaw direction.

The anticipatory behaviour of the head during turning is robust and is consistent despite changes in curvature and walking velocity (Vieilledent *et al*., 2001). A study on curved walking found that when walking velocity increased, trunk yaw oscillations increase, but the head shows comparatively less variance (Hicheur and Berthoz, 2005). This suggests that the head plays an important enough role during curved motion, that it will essentially ‘freeze’ to gain appropriate sensory information during motion, in line with motor redundancy theory (Bernstein, 1967). Prévost *et al.* (2002) showed that when altering walking speed while making 90° turns around corners, that head deviation occurred at approximately the same distance from the designated turn point regardless of walking speed, and concluded that this highlighted the role of environmental landmarks and egocentric reference frames in anticipatory orienting behaviour.

1.5.4 *Stepping characteristics*

The stepping actions during a turn are critical as they determine the width of base of support (BOS) which directly influences the strategies employed to maintain balance. Hase and Stein (1999) identified two types of walking turns used by healthy young adults: the ‘spin’ turn and the ‘step’ turn. The mechanism of the spin turn uses the leg on the turn side as an axis of rotation, with the ball of the foot serving as the sole BOS. The propulsive action at toe-off of the non-turn leg allows the body to rotate around the vertical axis on the ball of the foot followed by the non-turn foot being placed in the intended direction. The step turn uses small asymmetrical steps which slightly rotate both feet towards the new travel direction with each progressing step, thus maintaining a relatively wide BOS. During the spin, a small step is made by the non-turn foot resulting in both feet being slightly rotated towards the new travel direction. Asymmetrical stepping is continued until desired heading is achieved. Standing turns typically begin with either a step of the ipsilateral foot (i.e. right turn, right foot) or matched foot strategy or the contralateral foot (right turn, left foot) or unmatched strategy (Meinhart-Shibata *et al.,* 2005; Hong, Perlmutter and Earhart, 2009) (Figure 1-5).

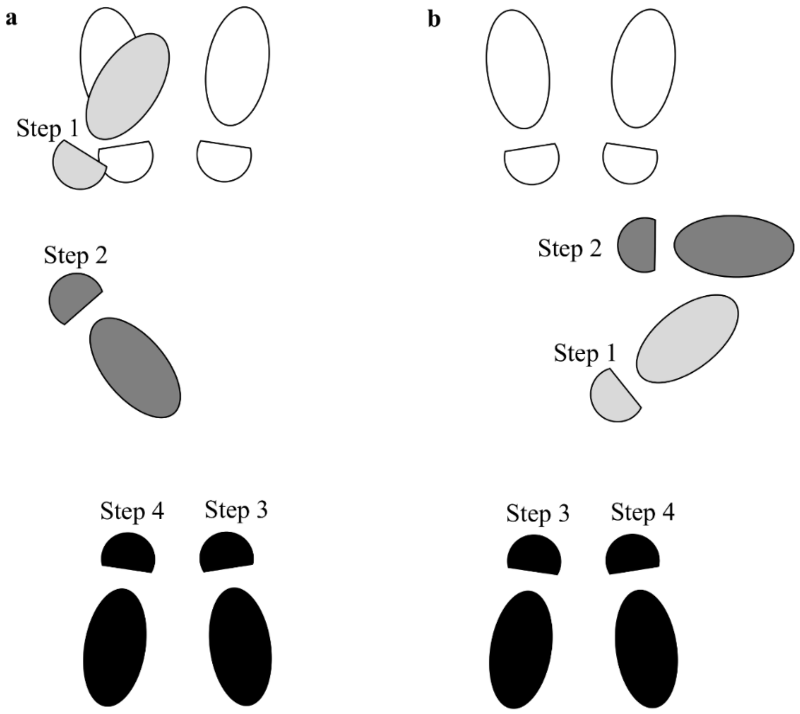

Figure 1-5: Recreated from Meinhart-Shibata *et al.*, 2005. Initial foot positions are in white and final foot positions are in black. a) An unmatched strategy standing turn and b) a matched strategy turn. The mechanism which determines foot placement during standing turns is not yet known.

During walking turns stride length decreases as the turn angle increases (Patla, Adkin and Ballard, 1999; Hollands, Sorensen and Patla, 2001); during circular walking, gait becomes asymmetrical, with the stride length of the internal foot decreasing comparative to the stride length of the external foot (Courtine and Schieppati, 2003b). Changes in the size of the BOS do not seem to have any significant effect on the reorientation of body segments according to the results of a 2008 study (Paquette *et al.*, 2008), which used two types of turns, a 'step out' turn which gave a wider BOS, and a cross-over turn that gave a narrower BOS. Despite the challenge of a narrow BOS, the sequence of body reorientation remained the same between turn types; the main effect found was a slightly different reorientation between the older and younger participants whereby COM displacement occurred before trunk roll in the younger adults, while it occurred after trunk roll in older adults.

Older adults typically adopt a step turn strategy much more often than the spin turn when walking at their natural pace, suggesting that maintaining a wider BOS is increasingly important with ageing (Akram, Frank and Chenouri, 2010). When able to choose between a ‘matched strategy’, for example when leading with the left foot to make a left turn, or an ‘unmatched’ strategy, older adults chose the unmatched strategy more often (Hong, Perlmutter and Earhart, 2009). Similar to the step turn, the unmatched strategy has an advantage over the matched strategy because the first step creates a wider BOS in the anterior-posterior plane. Ageing may also contribute to habits which decrease the BOS and challenge balance and stability. Older women have a tendency to bring their feet closer together, thus decreasing their BOS, when making turns to their non-preferred side, show more variable foot positioning than their younger counterparts, regardless of the turn direction and older women use a small ‘preparatory’ step in the anterior-posterior plane with the foot contralateral to the turn direction (Meinhart-Shibata *et al.*, 2005).

1.6 Summary

Turning is a whole-body process that begins with anticipatory movement of either the eyes or head which precedes reorientation of the trunk and feet towards the new travel direction. Anticipatory eye or head movements are seen whether visual information is available or removed, indicating that anticipatory gaze behaviour serves a function other than visual sampling. Stepping characteristics of turns often change with ageing, with a clear preference towards steps which will increase the base of support before further progression into the turn in older adults. In older individuals and neurological populations, turns often elicit falls. The majority of turning research has focused on these populations and have found deficits in eye movements and problems with body segment reorientation, however the mechanism resulting in falls in these individuals is not yet clear. More research on turning in young healthy individuals which determines normal turning behaviour and the necessary sensory input to successfully implement a turn will help elucidate the exact motor control mechanisms of turning and ultimately the mechanism failures which lead to falls.

The following experiments focus on investigations of sensorimotor control aspects during standing turns in young healthy adults to address the deficits in the existing body of literature and in particular the importance of the visual and oculomotor system during turning. Experiment 1, described in Chapter 3, aimed to determine the influence of turn-context by manipulating behavioural parameters including turn direction, turn amplitude and turn speed. We predicted that manipulations of turn amplitude and turn speed would cause systematic changes in oculomotor and turning behaviour. Experiment 2 (Chapter 4) examines the effects of separately removing visual input and preventing anticipatory eye movements on intersegmental coordination. We predicted that removing vision would have little effect on kinematics but that suppressing eye movements would cause disruptions in coordination. Experiment 3 (Chapter 5) examines the effects of manipulating neck proprioceptive input and its interactions with vision. We predicted that when neck muscle proprioception was manipulated during vision removal, that deviations in turn trajectory would occur, but that visual input would override inappropriate proprioceptive signals. Experiment 4 (Chapter 6) describes the effects of divided attention using a serial subtraction task. We predicted that in young healthy adults, divided attention while turning would potentially cause delays in turn onset, but would not significantly alter the characteristics of intersegmental coordination or nystagmus. The main aim of this was to provide a detailed investigation of eye movement characteristics and intersegmental coordination during whole-body turns in young healthy adults and to examine the effects of perturbing sensory systems and cognition in order to gain insights into the neural mechanisms which generate turning behaviour.

Chapter 2

General Methodology

2.1 Turn Protocol

Participants stood facing a projector screen (2.74 x 3.66 m Cinefold Projection Sheet, Draper, Inc, Spiceland., Indiana, USA) approximately four metres away, on which an animation demonstrating the required turn condition for the subsequent trial was shown followed by a short time interval and a ‘go’ signal which cued the participant to begin turning (Figure 2-1). The go signal was a visual signal (the background of the screen flashed bright green) for experiment 1 (Chapter 3) and an audio signal (a short tone) for experiments 2-4 (Chapters 4-6); the visual signal was changed to an audio signal as visual information was removed for some conditions in the experiments described in Chapters 3-4. Participants were told to imitate the direction and amplitude of the animated clock arm as accurately as possible, look straight ahead at the completion of the turn and return to the starting position upon instruction. Details on the specific experimental manipulations are discussed in the relevant chapters.

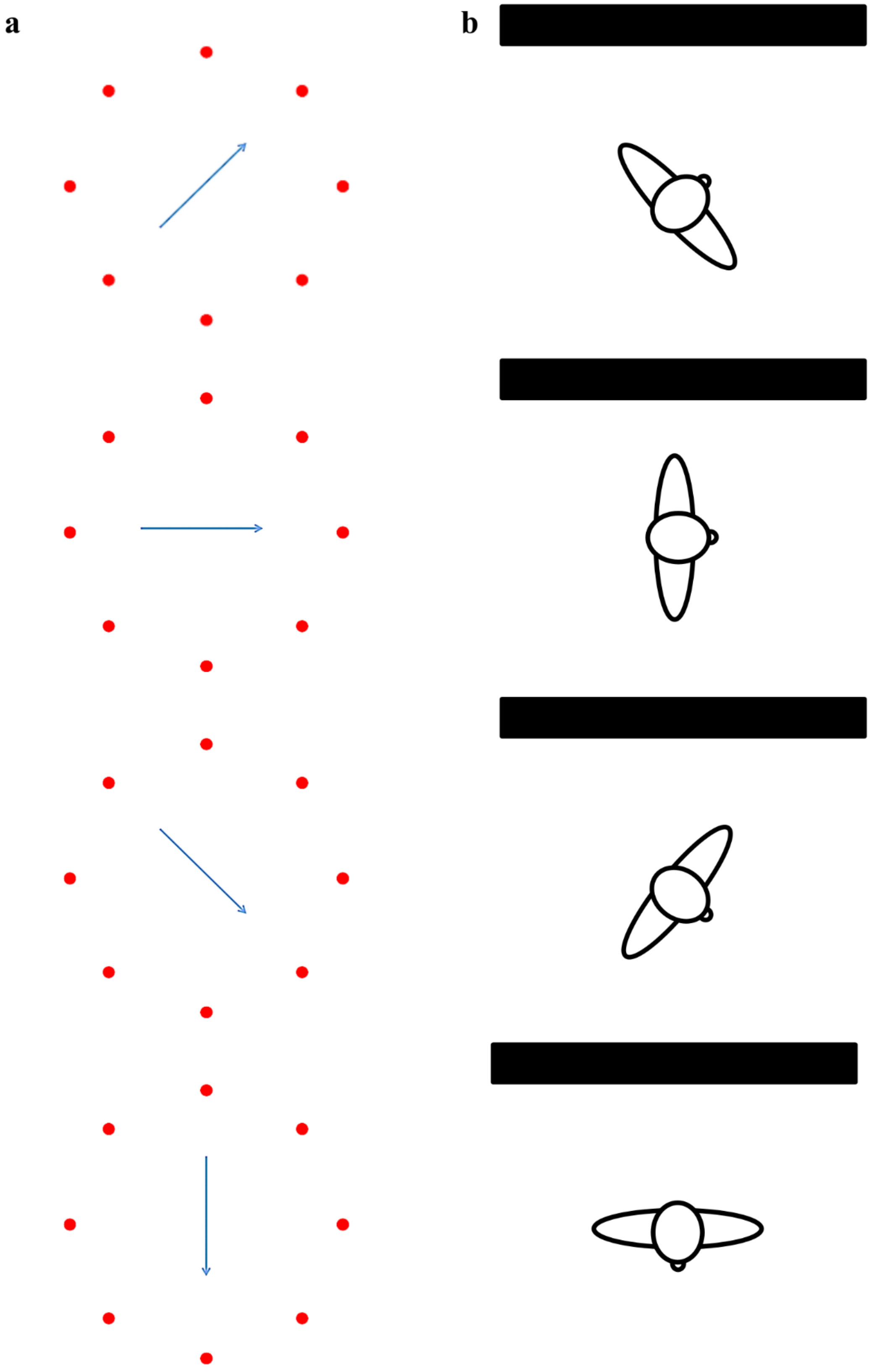

Figure 2-1: A schematic of the protocol; a) screen shots from the turn demonstration videos; b) the intended turn location for the corresponding screen shot (the black bar represents the projector screen). Turns were performed to spatially predictable *non-targeted* locations.

2.2 Turn Speed Familiarisation

Prior to the experimental session for experiments 2-4, a turn speed familiarisation phase was performed to limit the turn speed variability within and between the participants. The familiarisation phase began with the participant viewing the turn demonstration videos used within the experimental session, which was then followed by two audio signals separated by a time interval (Chapter 4 study: 1.5s for 90° and 2.5s for 180°; Chapters 5-6: 2s for 180°). The participant was instructed to begin turning on the first signal and reach the designated amplitude on the second signal. A minimum of two practice trials were performed to each direction and amplitude combination; practice trials were continued until both the investigator and participant were satisfied with the participant's performance.

2.3 Data collection

Participants were instrumented with 39 spherical reflective markers (14mm diameter) placed according to the Plug-in gait (PiG) setup (Vicon®, 2002). These markers were tracked using a Bonita motion analysis system (Vicon, Oxford, UK) at a sampling frequency of 200Hz. A Bluegain wireless electro-oculography (EOG) system (Cambridge Research System Ltd.) was used to record horizontal eye movements. Surface electrodes were placed on the outer canthi of each eye, as well as a reference electrode on the forehead (Figure 2-2). EOG signals were sampled at a frequency of 1000Hz. Data was synchronised using a LabVIEW programme which simultaneously illuminated an IRED within the capture volume which was identified by Vicon and marked the time point within the EOG data capture software. The two datasets were temporally lined up post-hoc during data analysis.

Figure 2-2: EOG setup. Three electrodes were placed on the participant, the reference electrode was placed in the centre of the forehead on the most prominent bony portion to minimise signal noise due to surface movement. The positive electrode was on the right outer canthi and the negative electrode was placed on the left outer canthi; a positive signal in the EOG displacement profile indicated eye movement to the right and negative signals indicated movement to the left.

2.4 Data analysis

Kinematic analysis. Angular displacement profiles for the head, thorax, pelvis and left and right feet in the global reference frame were determined from the PiG model in Vicon Nexus. The MATLAB (R2014a) programming environment was used to obtain all measures from the kinematic datasets. The analysis was limited to rotations within the yaw plane (i.e. rotations around the vertical axis) for experiment 1 (Chapter 3), analysis of pitch and roll rotation were included for experiments 2, 3 and 4 (Chapters 4-6). All kinematic data was passed through a dual low-pass 4th order Butterworth filter using a cut-off frequency of 6Hz. This value was chosen as it eliminates any unexpected high frequency noise while maintaining the measured curve without over-smoothing. Displacement profiles were differentiated to yield velocity and acceleration profiles for each segment.

Axial segment reorientation. Onset latencies for the axial segments (head, thorax and pelvis) were obtained using the displacement and velocity profiles. The criteria used to determine the rotation onset for each segment were an amplitude greater than 0° and less than 5° and a positive velocity; additionally, the amplitude and the velocity were required to be increasing following that time point. To avoid designating a sway movement as a rotation onset, the onsets were determined manually while viewing the displacement and velocity profiles for each segment and selecting the time which corresponded to the sustained rotation in the displacement profile (Figure 2-3a-b). This method was found to be more accurate than using an amplitude or velocity threshold alone which frequently indicated a time point which preceded the onset (e.g. sway movements) or followed the onset, such as during slow turns. The end of rotation was determined similarly, however the criterion was limited to the first zero crossing in the velocity profile following the end of the sustained rotation (see Figure 2-3c). Most movement following the rotation end time was minimal and was deemed to be a postural adjustment.

Normalisation procedures. Time normalised profiles for each axial segment were created from the shortest axial segment latency (normally the head yaw onset latency) to the final axial segment rotation end time. Normalisation was performed in this way so that the segments could be compared to each other over the whole course of all axial segment rotation. Using the normalised axial segment profiles, angular separation profiles were obtained from subtracting one profile from another, resulting in head-thorax, head-pelvis and thorax-pelvis profiles.

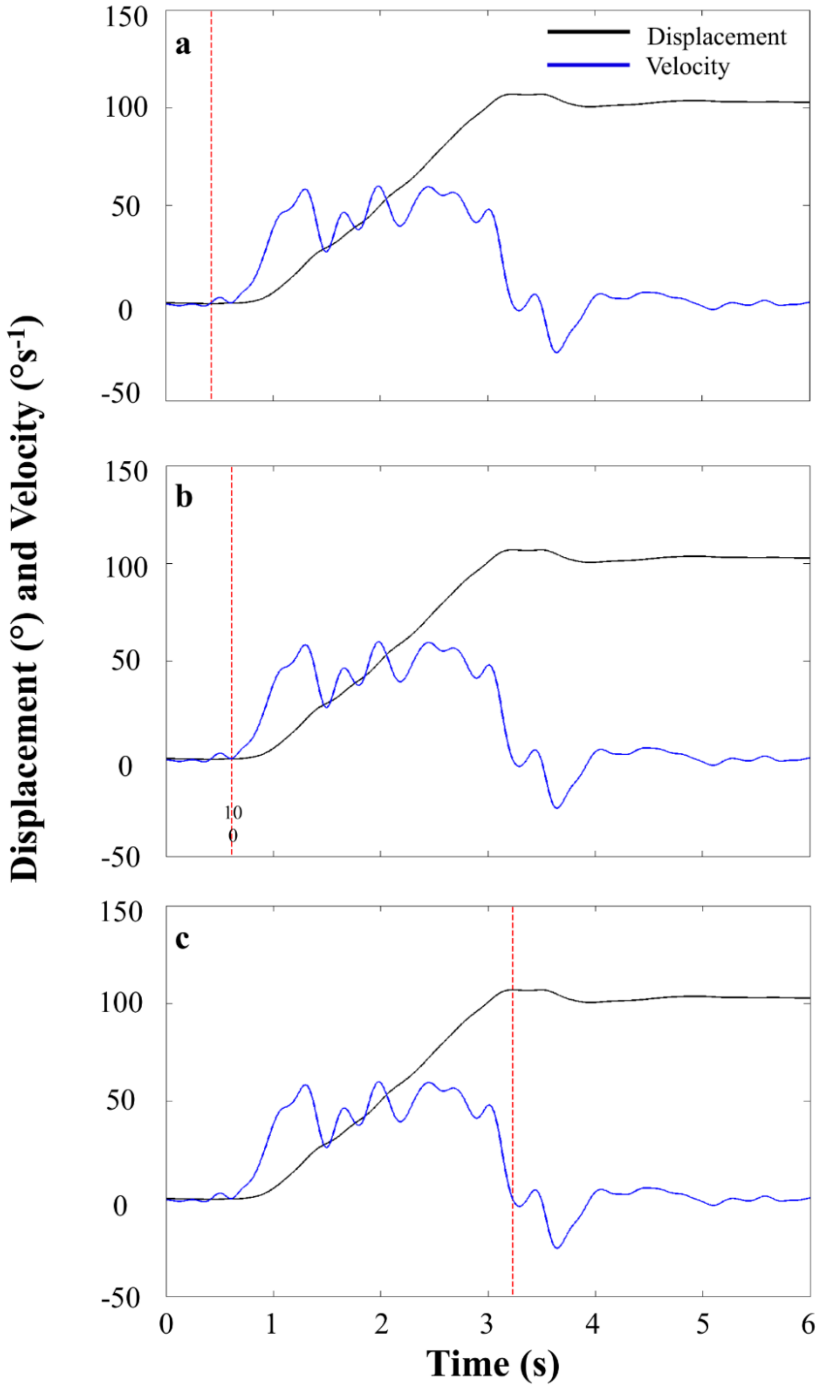

Figure 2-3: Sample yaw onset and end determination procedures from the head displacement and velocity profiles during a leftward 90° turn in no vision: a) time points which fit all criteria were viewed concurrently with the displacement and velocity profiles for the specific segment; small sway movements were frequently observed prior to the actual onset of turning. b) A time point fitting all the onset criteria which directly preceded the sustained rotation was determined as the onset latency for the segment. c) The first time point after the sustained rotation which was below $0°s^{-1}$ was determined as the end of the rotation for that segment. All onsets for the head, thorax and pelvis were determined in this manner.

Step analysis. Analysis was performed on all individual steps which occurred during the trial. Initially, an interval for each step was determined beginning with the positive zero crossing preceding and the negative zero crossing following a velocity which reached 15% of the maximum step velocity (Figure 2-4a). Each step onset was determined as the first frame of the step interval with a velocity greater than or equal to 30°s^{-1}. Step end time was determined as the first frame less than 30°s^{-1} following the peak velocity of the individual step. Individual step size was determined as the angular difference in foot position between step onset and step end, while placement amplitude was the total angular displacement at step end from the initial starting position. Step velocity and step acceleration were determined from the peaks in the designated profile from each step onset to step end.

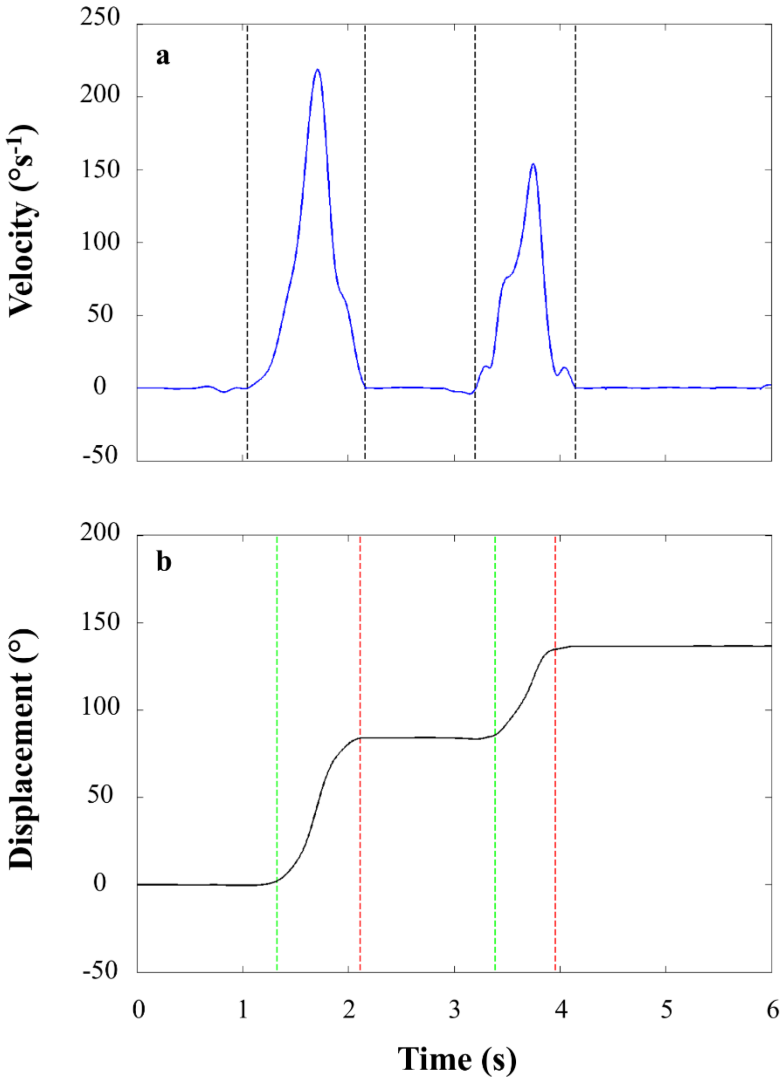

Figure 2-4: a) Step intervals were determined using paired zero crossings in the velocity profile, as shown by the dashed black lines to the left and right of each peak. b) Step onsets and end times were determined as the first time point to reach ≥30°s^{-1} (green dashed lines) after the first zero crossing and the first time point to reach ≤30°s^{-1} (red dashed lines) following the peak velocity within each step interval.

Electro-oculography analysis. Raw eye rotation data were converted from mV to degrees by using a linear regression of the eye versus head rotation using the VOR (Figure 2-5), whereby the degree of rotation of the eye is in approximate unity with the degree of rotation of the head. The MATLAB (R2014a) programming environment was used to obtain all measures from the EOG dataset. All EOG data was passed through a low-pass 4th order Butterworth filter using a cut-off frequency of 30Hz. This value was chosen to smooth the data only enough to determine discernible peaks and troughs for further analysis. Pilot analysis of data compared multiple cut-off frequencies between 10Hz and 50Hz. Angular velocity and acceleration profiles were created by differentiating the eye displacement profile.

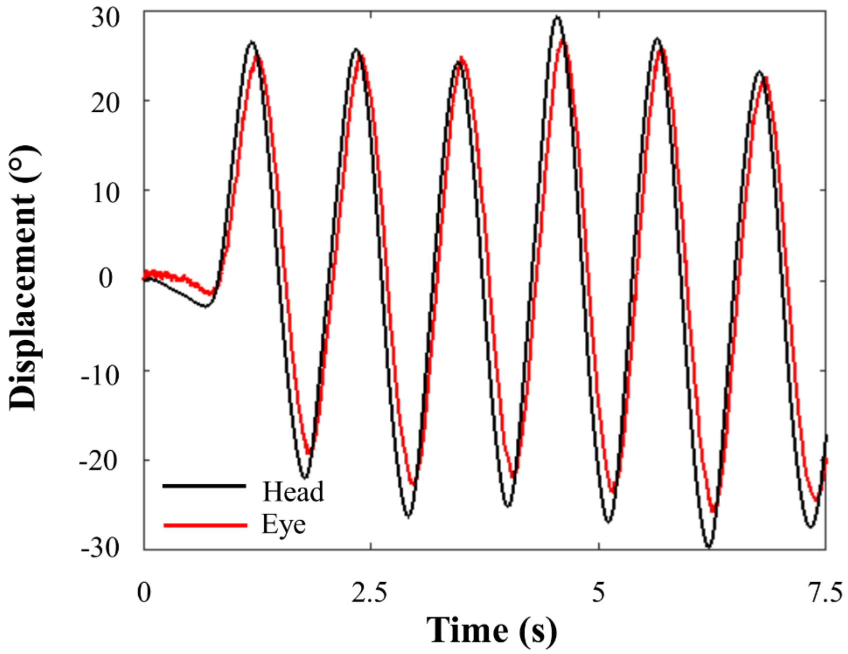

Figure 2-5: EOG Calibration. The calibrations trial required the participant to fixate a point and make sinusoidal head movements in the yaw plane. Eye position and head position data were temporally lined up and a portion of the data between a crest and a trough was selected for regression. VOR gain is near unity (i.e. the velocity of the eye and head are approximately equal and opposite), therefore the displacement of the eye will be approximately equal to the displacement of the head. A linear regression model can be used to fit the EOG data, measured in mV, to the positional measurements of the head (°), which accurately estimates the size of the eye movement in degrees.

Fast phase determination. Prior to analysing, EOG data for each trial was visually inspected concurrently with head onset and end times. Lower and upper limits for further analysis were manually determined to eliminate saccades and fixations which occurred prior to and following the turn (Figure 2-6a). From this selection of data, potential fast phases were determined using time intervals beginning with positive zero crossings and ending with negative zero crossings (Figure 2-6b). Time intervals were deemed to be a fast phase if the velocity was $\geq 30°s^{-1}$ and the change in amplitude was $\geq 1.5°$. The time of the positive zero crossing was determined to be the onset (Figure 2-6c) and the time of the negative zero crossing was deemed to be the end for each individual fast phase. Eccentric eye positions at fast phase onset and end were determined and all individual fast phase amplitudes, velocities and accelerations were obtained from fast phase onset to fast phase end time.

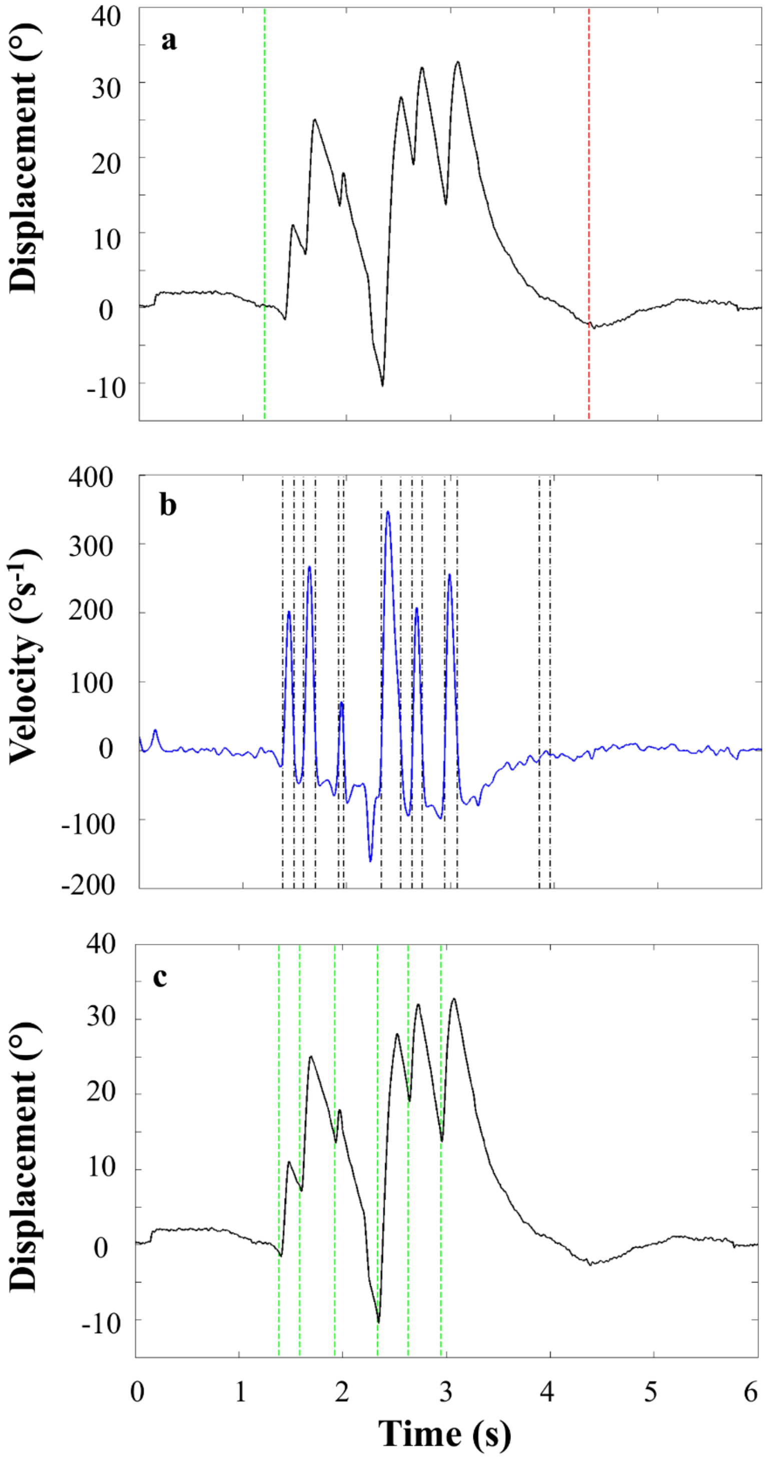

Figure 2-6: a) The nystagmus portion of the eye movement was selected to eliminate saccade/fixation combinations which were clearly outside the turn time based on head yaw onset (green dashed line) and end (red dashed line of head rotation). b) Time intervals were determined from the zero crossings in 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^{-1} and amplitude was ≥1.5°. Fast phase onsets were the positive zero crossings from the corresponding time interval (green dashed lines). Not shown: fast phase ends were the negative zero crossings from the time interval.

All data were reviewed and visually inspected for accuracy. Trials were excluded if any segment was not modelled throughout the course of the whole trial, filtering procedures were insufficient in reducing excessive noise or if specific measures were unable to be obtained using the limits determined by the customised script. Any alterations or additional analysis procedures are described within the data analysis section of the relevant chapter.

Chapter 3

Context-dependent spatiotemporal relationships between eye and whole-body kinematics during standing turns

3.1 Introduction

Whole body turns are usually characterized by a sequential ‘top down’ coordinated reorientation of the axial (i.e. head, trunk and pelvis) body segments starting with the eyes, head and ending with the feet (Grasso *et al.*, 1998; Hollands, Sorensen and Patla, 2001; Hollands, Ziavra and Bronstein, 2004; Anastasopoulos *et al.*, 2009; Reed-Jones *et al.*, 2009a; 2009b; Degani *et al.*, 2010). An initial saccadic eye movement in the turn direction is usually followed by a pattern of further eye movements termed nystagmus characterised by alternating phases of slow and fast movements which act to intermittently shift and stabilize gaze on environmental features in advance of the turn. The slow phase stabilizes gaze by compensating for head rotation and is driven by the VOR (Mishkin and Jones, 1966; Barnes, 1979); however, the role fast phase anti-compensatory eye movements play in the coordination of turning behaviour is relatively undefined. For example, it is unknown how eye movement characteristics during turning relate to body segment kinematics and how they change with different behavioural characteristics of a turn. The factors that determine the size or the frequency of the fast phases, specifically during nystagmus elicited during active whole-body motion are unknown. Furthermore, the main sequence, or the relationship between fast phase amplitude and both fast phase velocity and duration has not been characterised during whole-body rotations and how this relationship differs from nystagmus during passive rotation is unknown.

Understanding these relationships is important since eye movement behaviour and intersegmental kinematics are both altered in clinical populations with turning problems and a causal link between oculomotor deficits and turning dysfunction has been suggested (Lohnes and Earhart, 2011). PD patients turn more slowly; make slower and smaller initial fast phase eye movements; and make more total fast phase eye movements than healthy individuals during standing turns. However, the effect of modulating turn speed or turn amplitude on nystagmus characteristics and the spatiotemporal relationships between the eyes and the body segments in young healthy individuals is unknown, therefore it is not possible to determine whether differences between patient groups are due to pathology (e.g. oculomotor dysfunction) or simply altered behaviour (e.g. turn speed). Furthermore, while there is a strong correlation between the onset latencies of the eyes, axial body segments and stepping movements which suggest top-down control during turning initiation, little is known about the control mechanisms relating to subsequent foot rotations or foot placement during whole-body turns (Anastasopoulos *et al.*, 2009).

We aimed to provide a body of normative data from young healthy individuals which reflects the changes induced by altered turning behaviour; specifically turn amplitude and turn speed, which can be used for future comparisons with ageing and clinical populations. Our objectives were to: a) determine whether rotation onset latency- a measure commonly used to describe intersegmental coordination- is representative of intersegmental coordination during the turn by comparing onset latency measurements with measurements of intersegmental coordination taken throughout the duration of the turn b) examine how eye movement characteristics change with turn parameters and c) investigate the biomechanical factors that determine foot stepping and foot placement characteristics during turning. We predicted that we would identify consistent spatiotemporal relationships between the eye and axial body segment rotations and feet which could represent neural synergies controlling whole-body turns.

3.2 Methods

3.2.1 Participants

Nine healthy young men, mean age 24.64 years (± 2.78 *SD*) volunteered for the study. The experimental protocol was approved by the Liverpool John Moores Research Ethics Committee (REC) and all participants gave written and informed consent. Participants were excluded if neurological, musculoskeletal, or cognitive impairments were reported, or if taking medication for anxiety and/or dizziness or if they used an assistive walking device.

Cognitive function was tested using the Mini Mental State Examination (MMSE), where a score of 26 or above indicates intact cognitive function (Folstein, Folstein and McHugh, 1975). Additional cognitive testing was assessed using the Trail Making Test parts A and B; a completion time of ≥78 seconds and ≥273 seconds, respectively, indicate deficient cognitive function (Reitan, 1958). Visual testing was performed using the Freiburg Vision Test (FrACT) and included an examination for monocular and binocular visual acuity using the Landolt C test (Bach, 1996). All participants had normal or corrected to normal visual acuity (20/20 or better). Additionally, a general health survey (SF-36) was completed by all participants on the day of testing (Brazier *et al.*, 1992; Ware and Sherbourne, 1992).

3.2.2 Protocol

The experimental conditions included turn direction, turn amplitude and turn speed. The specific turn condition for each trial was demonstrated via animations projected onto a large screen in front of the participant. The animations showed a clock face with a hand/arrow that moved in the desired direction (left or right), amplitude (45°, 90°, 135° or 180°) and speed (‘moderate’: arm moved at 90 $°s^{-1}$ and ‘fast’: arm moved at 180 $°s^{-1}$) (Figure 2-1). Participants were told to imitate the direction, amplitude and velocity of the animated clock arm as accurately as possible, look straight ahead at the completion of the turn and to return to the starting position upon instruction. Trial order was fully randomised for each participant. A total of 5 trials were recorded for each condition for a total of 80 trials.

3.2.3 Statistical analysis

The statistical package SPSS (22.0) was used for all statistical procedures. A 2 x 2 x 4 repeated measures analysis of variance (RM ANOVA) was performed on all dependent variables with direction (left or right), speed (moderate or fast) and amplitude (45°, 90°, 135° or 180°) as repeated measure factors. No effects of turn direction (left versus right) were found on any measures therefore data was collapsed resulting in a 2 x 4 RM ANOVA design. Pearson’s Product moment correlation was used to determine the strength of the relationships between the dependent variables. Frequency distribution analysis was performed on all fast phase characteristics and Kolmogorov-Smirnov Z (K-S Z) was run to determine differences between the distributions from each experimental condition. Main sequence analysis was performed on fast phase data for all experimental conditions; correlation coefficients were then compared using a Fisher transformation. All mean values are presented with standard deviations unless otherwise stated. Statistical significance was set at $P<.05$. A Bonferroni's correction was used for multiple comparisons.

3.3 Results

3.3.1 Segment onset latencies

Figure 3-1 shows the turn displacement from one trial, whereby the axial segments start to reorient at approximately the same time, followed by the reorienting fast phase and finally the stepping of the feet. The typical sequence of segment reorientation began with the head, followed by the thorax, then the pelvis or eyes, and finally the leading and trailing foot; this sequence was preserved for each of the amplitudes and both of the speed conditions (Figure 3-2). Pearson's product moment correlation analysis revealed highly significant correlations between the onset latencies of all segments (Table 3-1). There was a significant main effect of turn speed on mean onset latency for all segments (eye: $F_{(1,8)} = 24.94$, $P=.001$; head: $F_{(1,8)} = 33.39$, $P<.001$; thorax: $F_{(1,8)} = 36.03$, $P<.001$; pelvis: $F_{(1,8)} = 47.95$, $P<.001$; leading foot: $F_{(1,8)} = 66.53$ $P<.001$; trailing foot: $F_{(1,8)} = 46.39$, $P<.001$). Onset latencies were shorter during fast speed trials than moderate speed trials for all turn amplitudes (Figure 3-2). A significant main effect of turn amplitude was found for eye ($F_{(1,8)} = 4.97$, $P=.008$), leading foot ($F_{(1,8)} = 3.76$, $P=.024$) and trailing foot onset latencies ($F_{(1,8)} = 7.84$, $P=.001$). Post hoc pairwise comparisons revealed that the effects of amplitude were limited to the fast trials only and there were only significant differences between 45° and 180° turns ($P=.008$), whereby eye rotation onset began significantly earlier during 45° turns. Pairwise comparisons found the effects of turn amplitude on the lead foot onset were limited to differences between turns to 90° and 180° (*P*=.047) in the fast condition only, which showed that the leading foot onset occurred earlier during turns to 180°. Significant effects of turn amplitude on trailing foot onset occurred only in the moderate speed trials and were limited to between turns to 45° and 135° (*P*=.028) and 90° and 135° (*P*=.05); there was a general trend which showed that onsets became earlier with increased turn amplitude. There were no significant interactions between turn speed and turn amplitude for any segment onset latency.

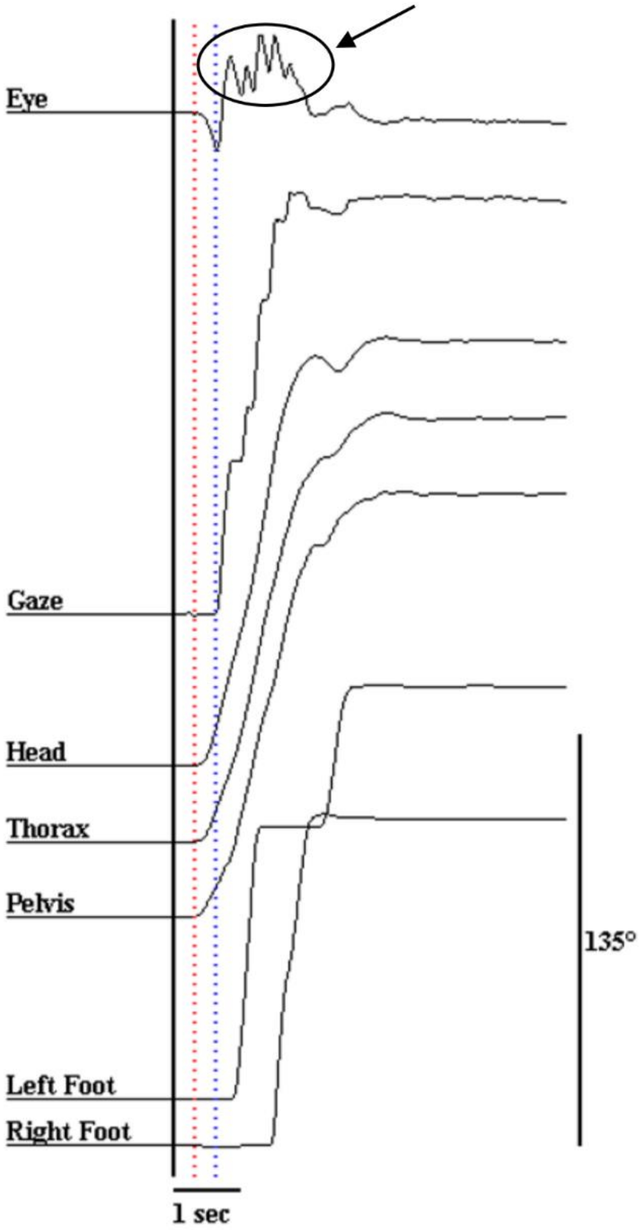

Figure 3-1: Representative displacement profile from one participant for a 135° turn. The solid black line represents the time of the 'go' signal which cued the participant to begin turning. The dotted red and blue lines represent the head and eye rotation onset latencies, respectively. Frequently, the initial displacement of the eye was a slow rotation away from the turn direction followed by the initial fast phase towards the turn direction. Arrow indicates that the eye was eccentrically rotated away from centre orbit (primary position) and towards the turn direction for the majority of the duration of the turn.

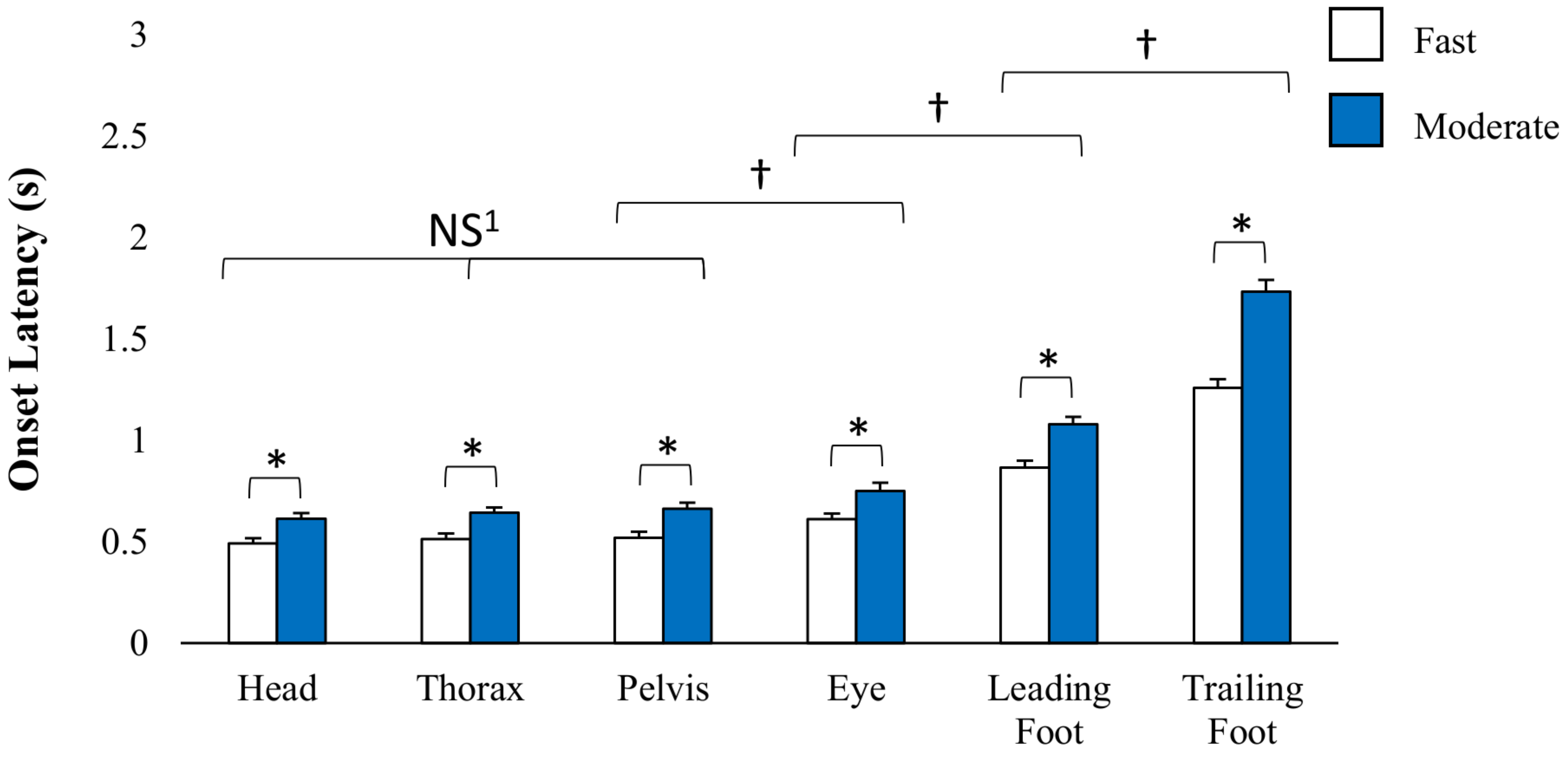

Figure 3-2: Mean onset latencies with amplitude conditions collapsed. There was a significant main effect of speed condition on the timing of rotation onset for all segments. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between speed conditions, and brackets with daggers represent statistically significant differences between segments. [1] There were no statistically significant differences between the onset latencies of any of the axial segments indicating the turn was initiated *en bloc*.

Table 3-1a

Mean onset latencies (ms) for the fast speed trials for all turn amplitude conditions and the coefficient of determination (R^2) from Pearson's product moment correlations between the onset latencies of the eye, axial body segments and foot rotations from all participants during fast speed trials.

		45	90	135	180		Eye	Head	Thorax	Pelvis	Leading Foot	Trailing Foot
Eye	Fast	552 ± 167	625 ± 191	623 ± 198	640 ± 216	Pearson correlation		0.72	0.63	0.61	0.43	0.24
						Sig. (2-tailed)		<.001	<.001	<.001	<.001	<.001
Head	Fast	478 ± 161	523 ± 196	485 ± 178	482 ± 180	Pearson correlation	0.72		0.90	0.81	0.61	0.36
						Sig. (2-tailed)	<.001		<.001	<.001	<.001	<.001
Thorax	Fast	502 ± 167	536 ± 196	515 ± 188	505 ± 177	Pearson correlation	0.63	0.90		0.89	0.72	0.44
						Sig. (2-tailed)	<.001	<.001		<.001	<.001	<.001
Pelvis	Fast	499 ± 173	545 ± 208	519 ± 207	516 ± 195	Pearson correlation	0.61	0.81	0.89		0.69	0.43
						Sig. (2-tailed)	<.001	<.001	<.001		<.001	<.001
Leading Foot	Fast	821 ± 158	823 ± 190	795 ± 208	748 ± 185	Pearson correlation	0.43	0.61	0.72	0.69		0.80
						Sig. (2-tailed)	<.001	<.001	<.001	<.001		<.001
Trailing Foot	Fast	1266 ± 250	1230 ± 244	1173 ± 267	1110 ± 238	Pearson correlation	0.24	0.36	0.44	0.43	0.80	
						Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	

N = 334

Table 3-1b

Mean onset latencies (ms) for the moderate speed trials for all turn amplitude conditions and the coefficient of determination (R^2) from Pearson's product moment correlations between the onset latencies of the eye, axial body segments and foot rotations from all participants during moderate speed trials.

		45	90	135	180		Eye	Head	Thorax	Pelvis	Leading Foot	Trailing Foot
Eye	Moderate	729 ± 273	774 ± 304	747 ± 270	753 ± 239	Pearson correlation		0.69	0.57	0.52	0.49	0.39
						Sig. (2-tailed)		<.001	<.001	<.001	<.001	<.001
Head	Moderate	601 ± 199	635 ± 194	604 ± 172	616 ± 166	Pearson correlation	0.69		0.84	0.76	0.61	0.44
						Sig. (2-tailed)	<.001		<.001	<.001	<.001	<.001
Thorax	Moderate	626 ± 186	657 ± 194	630 ± 161	659 ± 178	Pearson correlation	0.57	0.84		0.89	0.68	0.44
						Sig. (2-tailed)	<.001	<.001		<.001	<.001	<.001
Pelvis	Moderate	633 ± 191	681 ± 215	664 ± 188	678 ± 187	Pearson correlation	0.52	0.76	0.89		0.63	0.40
						Sig. (2-tailed)	<.001	<.001	<.001		<.001	<.001
Leading Foot	Moderate	1008 ± 182	1005 ± 188	973 ± 173	995 ± 167	Pearson correlation	0.49	0.61	0.68	0.63		0.80
						Sig. (2-tailed)	<.001	<.001	<.001	<.001		<.001
Trailing Foot	Moderate	1653 ± 285	1593 ± 279	1529 ± 257	1537 ± 257	Pearson correlation	0.39	0.44	0.44	0.40	0.80	
						Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	

N = 339

3.3.2 Eye-head latency difference

Frequency analysis on the difference between the onset of eye and head rotation was performed. Cumulative distributions revealed that eye rotation preceded head rotation in only 13% of trials (Figure 3-3), while in the majority of trials the initial fast phase onset occurred between 100 and 200ms *after* head rotation. RM ANOVA revealed a main effect of amplitude ($F_{(3,\ 24)} = 7.39$, P=.001) on the eye-head latency difference. Post hoc analysis showed the amplitude effects were limited to differences between turns to 45° and all other turn amplitudes in the fast speed condition only.

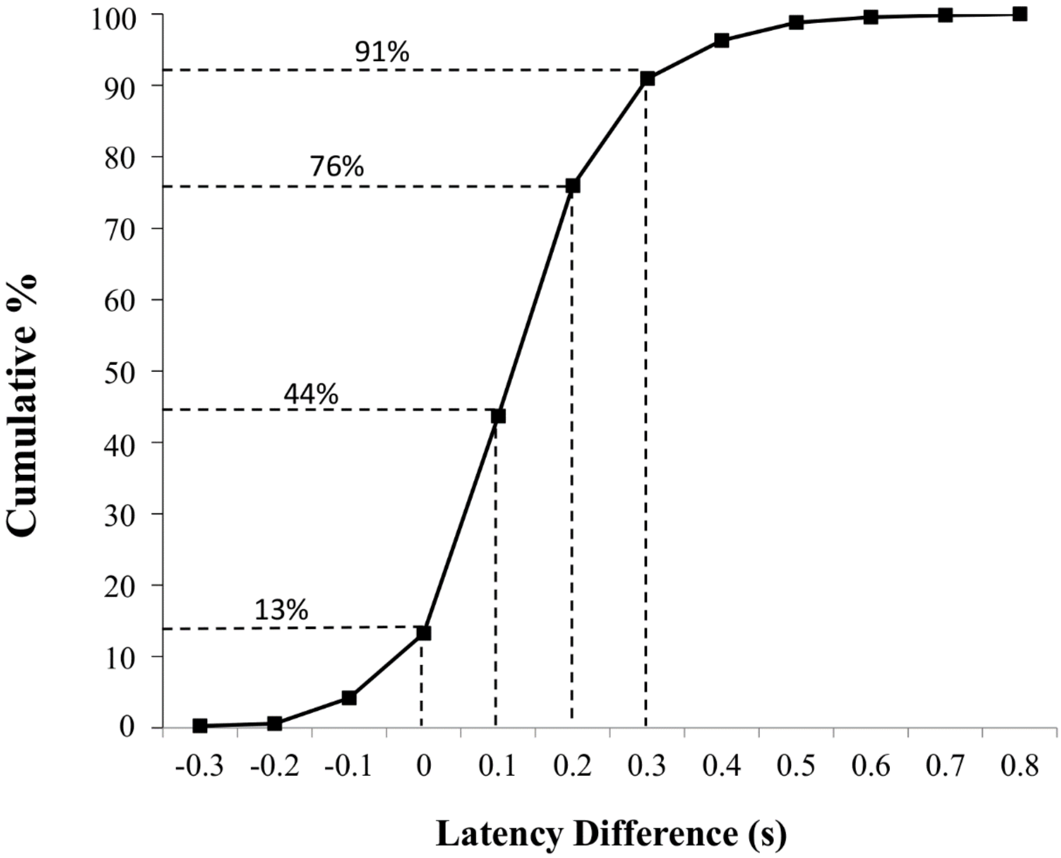

Figure 3-3: The difference between the onset of head rotation and the initial fast phase. Negative latency differences indicate that the onset of rotation of the eye preceded the onset of rotation of the head.

3.3.3 Inter-segmental relationships

RM ANOVA revealed significant interactions between amplitude and speed on the peak head-thorax ($F_{(3, 24)} = 15.22$, $P<.001$) and peak head-pelvis ($F_{(3, 24)} = 19.68$, $P<.001$) angular separation (Figure 3-4). Post-hoc tests reveal that peak segment separation increased with both increased turn amplitude and increased turn speed, but there were no significant differences in segment separation between turn to 135° and 180° in either speed condition.

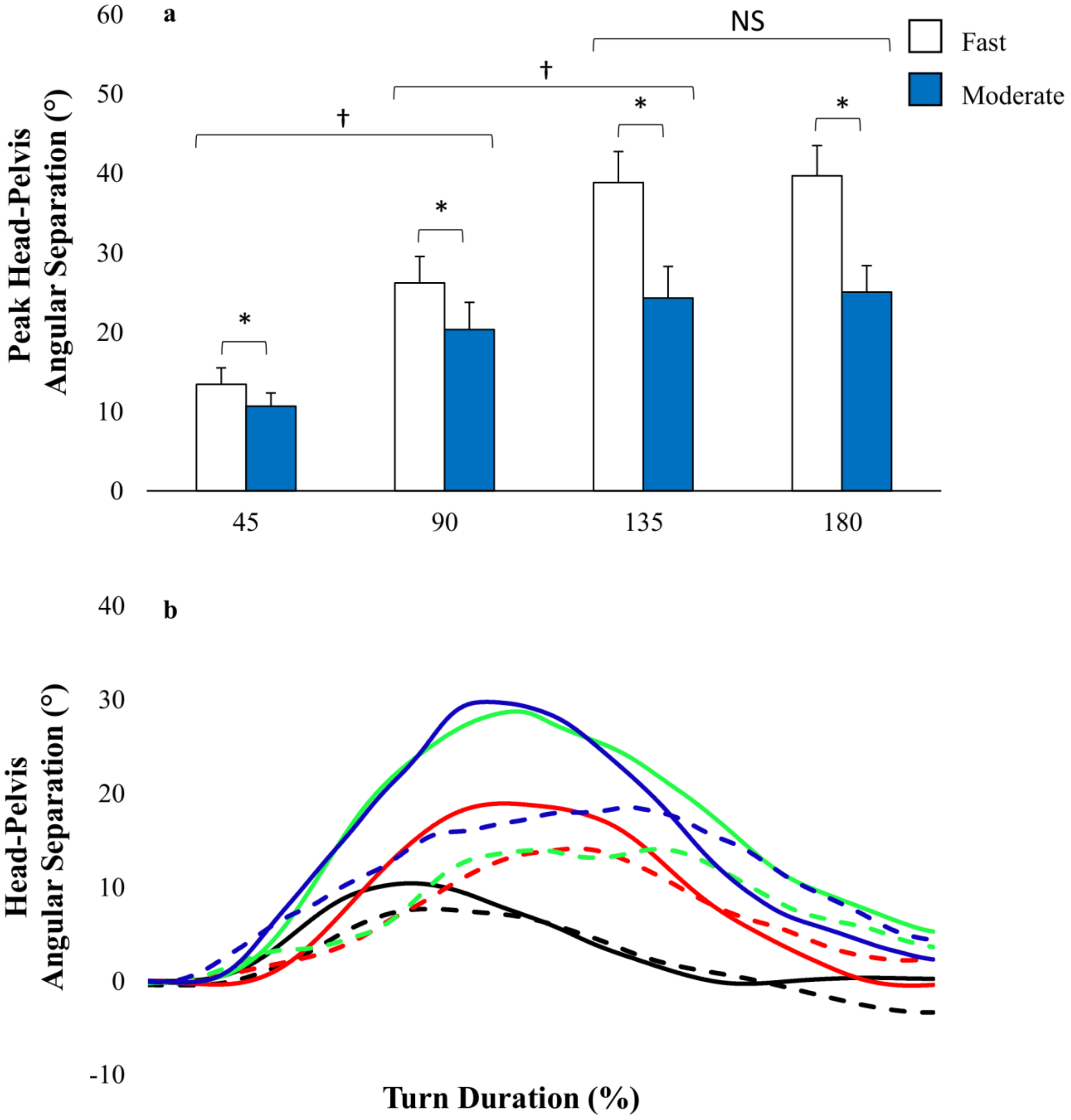

Figure 3-4: a) Mean peak angular separation between the head and the pelvis. Differences in mean angular separation were statistically significant between speed conditions for all amplitudes. Statistically significant differences were observed between all amplitudes except between 135° and 180°. b) Representative head-pelvis angular separation plots from one participant (see section 2.4 normalisation procedures for methods). The peak of each curve was determined and subsequently used for analysis. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between speed conditions and brackets with daggers represent statistically significant differences between amplitude conditions.

Figure 3-2 shows mean onset latencies for all segments for all participants; in both fast and moderate speed conditions, on average the axial segments began rotating at approximately the same time or *en bloc*. However, visual inspection of displacement curves showed that after the onset of rotation, generally the head increases its displacement at a faster rate than either the thorax or the pelvis. Correlation analysis between turn speed and peak angular segment separation revealed significant positive relationships between the head and thorax ($R^2 = .56$, $P<.001$) and the head and pelvis ($R^2 = .58$, $P<.001$). Figure 3-5 shows the regression analysis between peak head velocity and peak angular separation between the head and pelvis which predicts that turns performed above peak head velocities of approximately 85°s^{-1} will result in separation between the head and pelvis during the turn and that the peak angular separation increases with increasing turn speed.

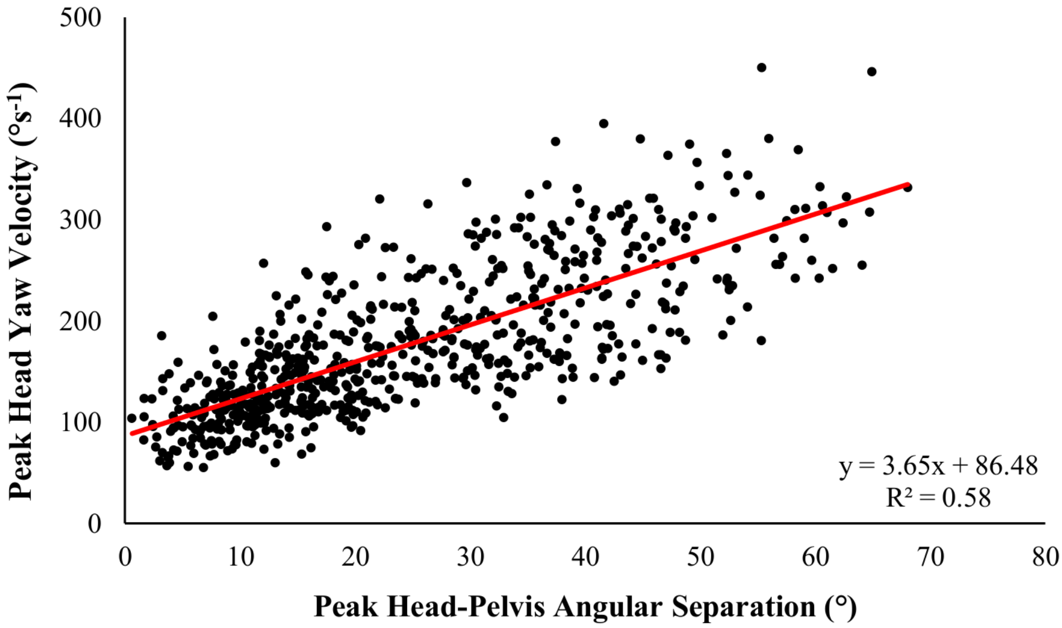

Figure 3-5: Regression analysis between the peak head yaw velocity and the peak angular separation between the head and the pelvis.

3.3.4 Fast phase characteristics

Means were calculated for the initial fast phase amplitude and velocity as well as the maximum fast phase amplitude and peak fast phase velocity (Table 3-2). A main effect of turn speed was found on the initial fast phase amplitude ($F_{(1, 8)} = 15.96$, P=.004), initial fast phase velocity ($F_{(1, 8)} = 16.82$, P=.003) and the peak fast phase velocity ($F_{(1, 8)} = 5.90$, P=.041). A main effect of turn amplitude was found on the maximum fast phase amplitude ($F_{(3, 24)} = 6.78$, P=.002) and peak fast phase velocity ($F_{(3, 24)} = 14.36$, P<.001). An interaction of turn speed and turn amplitude was found on the peak fast phase velocity ($F_{(3, 24)} = 5.72$, P=.004). Post hoc tests showed the effects of amplitude were limited to moderate speed turns only, which showed that peak fast phase velocity increased with increased turn amplitude. Speed caused significant differences between turns to 90° (P=.017) and 180° (P=.005), which showed that peak fast phase velocity was significantly *faster* during moderate turns than during fast turns.

Nystagmus fast phase frequency (NFPF) was calculated as the number of fast phases elicited divided by the duration of the interval between the eye onset latency and the cessation of head movement. RM ANOVA was performed on the NFPF resulting in a main effect of amplitude ($F_{(3, 24)} = 31.26$ P<.001), but not speed (see bracket Table 3-2). Post hoc comparisons found that NFPF was significantly higher (P=.023) during 180° turns than 45° turns during fast speed trials. During moderate trials, there was a general increase in NFPF with increasing turn amplitude, however, NFPF in 45° trials did not differ significantly from 90° trials and NFPF in 135° did not differ significantly from 180° trials, all other pairs were significantly different. There was no correlation between NFPF and peak head velocity. Figure 3-6 shows representative nystagmus data from one participant.

Table 3-2

Mean and standard deviations for initial and maximum/peak fast phase characteristics as well as fast phase frequency measurements.

		45	**90**	**135**	**180**
Initial Fast Phase Amplitude (°)	Fast	19.77 ± 10.78	20.95 ± 12.5	21.62 ± 12.00	24.67 ± 11.08
	Moderate	18.33 ± 12.05	15.62 ± 11.89	14.61 ± 11.19	16.60 ± 12.30
Maximum Fast Phase Amplitude (°)	Fast	23.50 ± 7.36	27.43 ± 7.12	27.64 ± 7.26	29.06 ± 7.02
	Moderate	25.02 ± 7.63	26.10 ± 6.88	26.07 ± 9.00	29.92 ± 9.06
Initial Fast Phase Velocity (°s^{-1})	Fast	243.89 ± 97.69	231.27 ± 72.60	246.73 ± 78.16	250.64 ± 64.40
	Moderate	216. 91 ± 86.34	203.39 ± 81.30	208.22 ± 78.24	221.47 ± 72.23
Peak Fast Phase Velocity (°s^{-1})	Fast	275.18 ± 86.02	269. 17 ± 61.63	309.36 ± 75.09	305.28 ± 64.28
	Moderate	261.73 ± 70.13	300.51 ± 77.61	320.32 ± 74.81	359.84 ± 74.56
Initial Fast Phase Acceleration (°s^{-2})	Fast	19256.44 ± 8125.59	19940.81 ± 6944.80	23289.86 ± 7899.06	23326.55 ± 8590.51
	Moderate	20245.58 ± 8080.48	21364.73 ± 8416.42	21736.39 ± 8348.62	22765.97 ± 9534.28
Peak Fast Phase Acceleration (°s^{-2})	Fast	23862.09 ± 8748.81	24964.74 ± 7972.10	31830.94 ± 8692.33	34582.80 ± 8675.10
	Moderate	24684.32 ± 7331.25	30136.52 ± 8006.81	34476.58 ± 8097.95	40264.35 ± 11466.83
Number of Fast Phases (N)	Fast	2.07 ± 1.18	2.49 ± 1.19	4.26 ± 1.99	4.78 ± 1.5
	Moderate	2.52 ± 1.37	3.61 ± 1.71	6.30 ± 1.97	7.35 ± 1.99
Nystagmus Fast Phase Frequency (Hz)	Fast	2.14 ± 0.97	2.21 ± 0.92	2.84 ± 1.09	3.10 ± 0.93
	Moderate	1.85 ± 0.88	2.28 ± 0.91	3.02 ± 0.77	3.04 ± 0.70

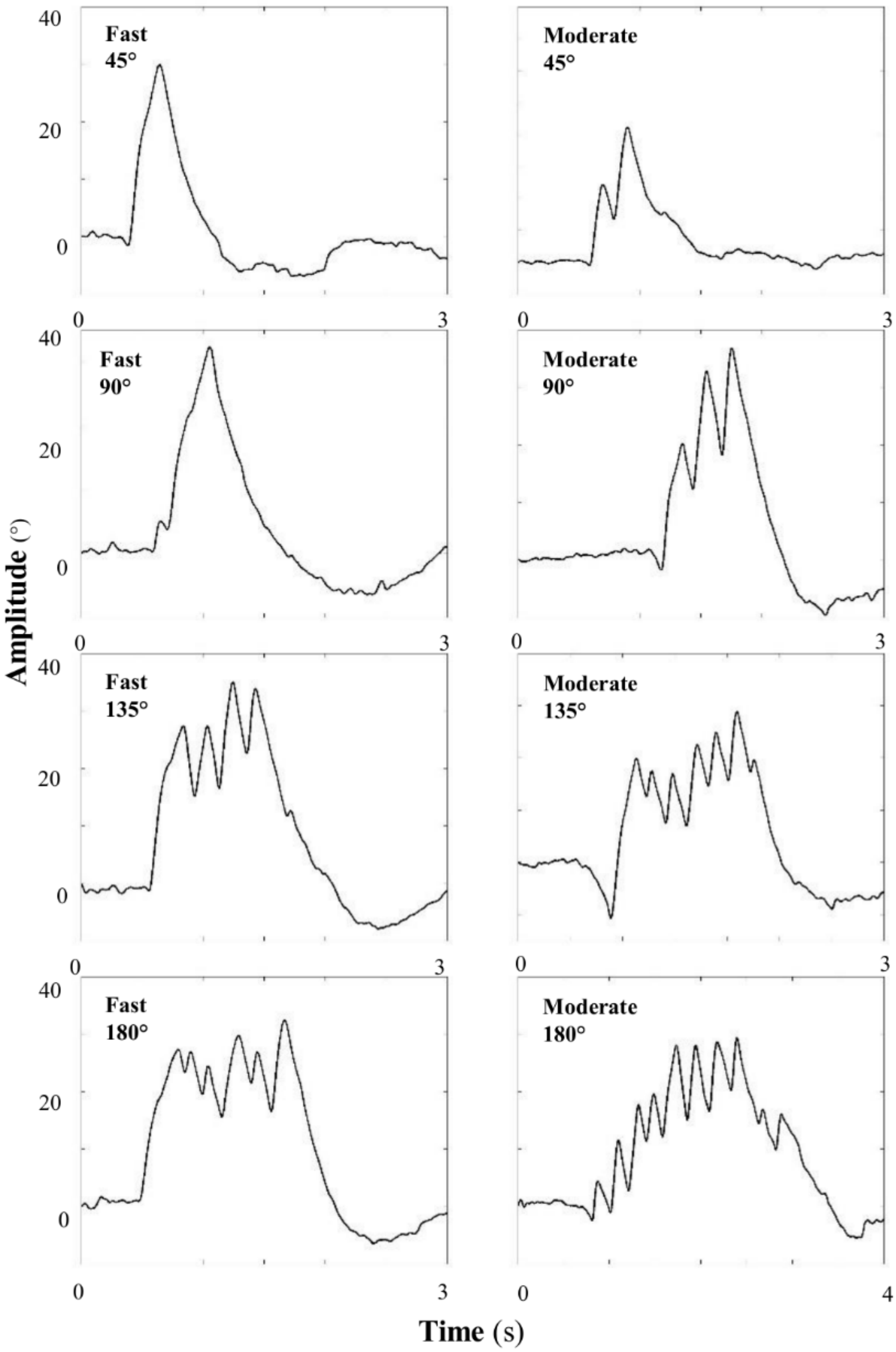

Figure 3-6: Representative eye displacement profiles for each speed and amplitude condition from one participant. There is a general trend which shows the number of fast phases increases with increasing turn amplitude and increased with decreasing turn speed. Additionally, the initial fast phase amplitude is usually larger during faster turns.

Main sequence analysis was performed by plotting peak fast phase velocity as a function of maximum fast phase amplitude (Figure 3-7) for each turn amplitude and turn speed. A power function was used to fit the data according to that performed by Kaminiarz *et al.* (2009) and a Fisher transformation was run to compare the correlation coefficients between speed conditions for each turn amplitude. No significant differences were found between turn speed conditions for any turn amplitude, therefore speed conditions were collapsed and subsequent correlation coefficients for each turn amplitude were compared. No significant differences were found between turn amplitudes.

Frequency distribution analysis was performed on the eye-in-orbit position at the beginning and end of each fast phase and found that the eye position at fast phase onset was in primary position (0° in orbit) or eccentrically rotated away from the turn direction for approximately 28% of all fast phases (Figure 3-8a). Eye-in-orbit position at the end of the fast phase was eccentrically rotated 30° or less towards the turn direction in 74% of all fast phases (Figure 3-8b). Only 2% of all fast phases ended at eye-in-orbit position which was eccentrically rotated away from the turn direction. Frequency distribution analysis was also performed on the amplitude and velocity of all fast phases elicited throughout the experiment. A positively skewed distribution was found showing that nearly a third of fast phases elicited were 5° or smaller, 65% were 15° or smaller and approximately 91% were 30° or smaller (Figure 3-8c). Analysis of fast phase velocity found a normal distribution and that approximately 80% of fast phases were $300°s^{-1}$ or slower (Figure 3-8d). K-S Z was performed on all distributions and found no significant differences between moderate and fast distributions.

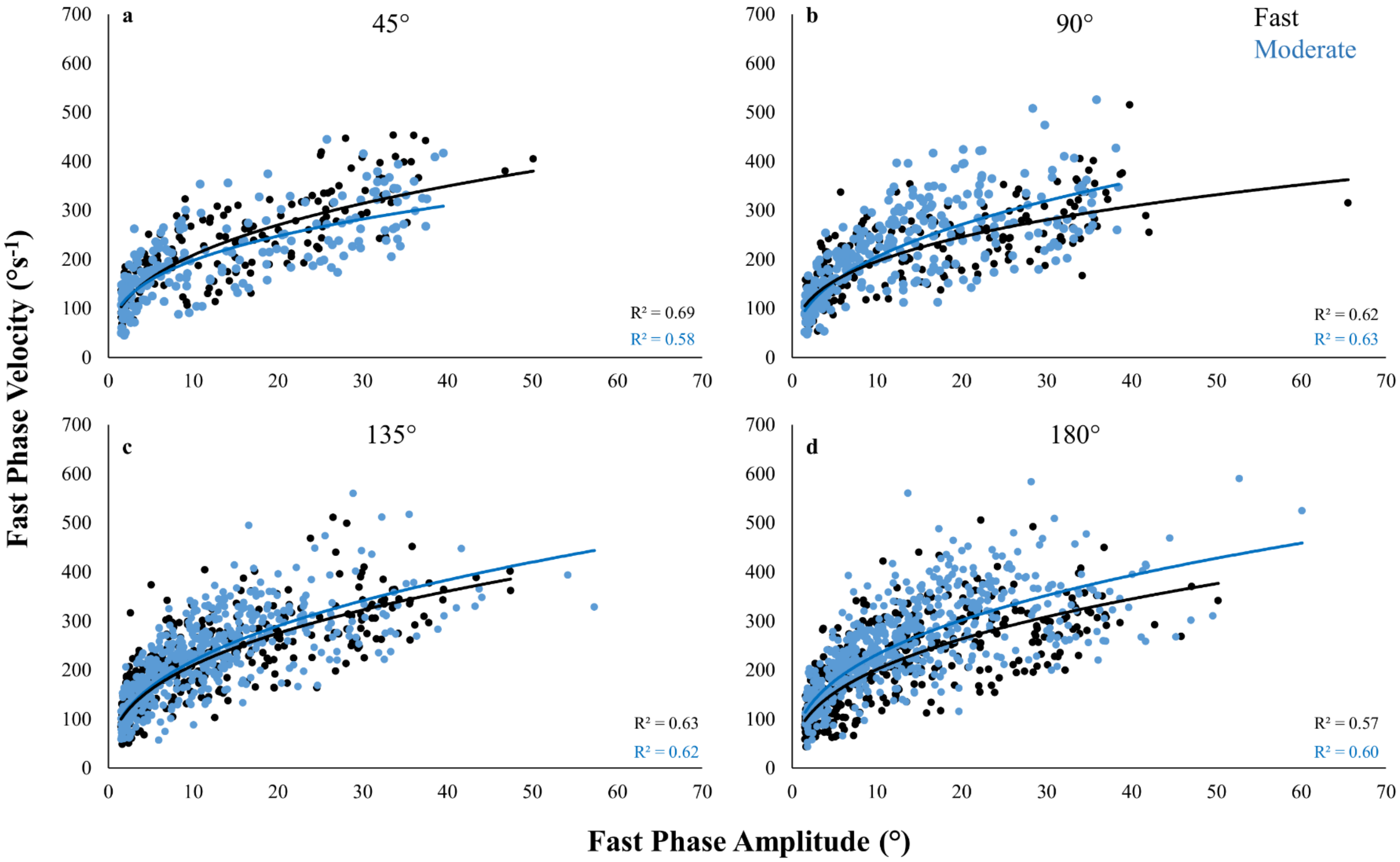

Figure 3-7: Comparison of the main sequences for all turn amplitude and during both fast (black) and moderate (blue) speed turns. An inverse power function was used to fit each data set. Fisher transformation found no significant differences between either turn speed or turn amplitude.

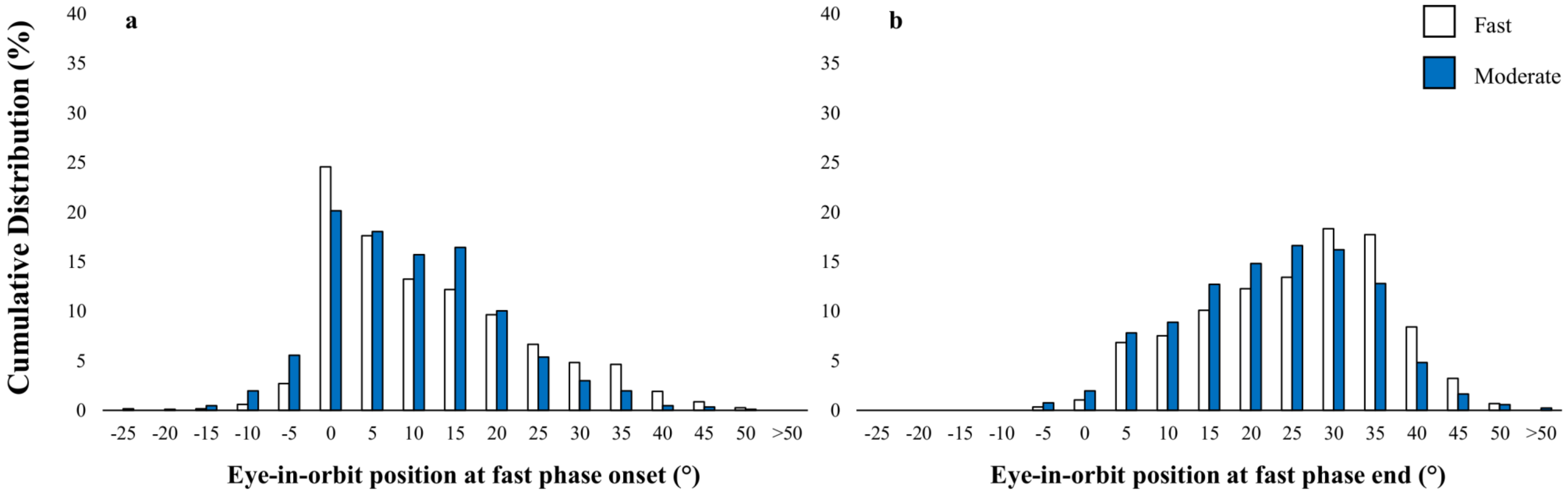

Figure 3-8a-b: Cumulative frequency distributions for each speed condition; a) distribution of eye-in-orbit positions at the onset of each fast phase showed that majority of fast phases were elicited from at or near the central orbital position (0°). b) Distribution of eye-in-orbit position at the end of each fast phase which show that the eye-in-orbit positions for the fast turn condition are slightly more eccentric. K-S Z found no statistically significant differences between fast and moderate speed condition cumulative distributions of fast phase eye-in-orbit positions at either fast phase onset or fast phase end.

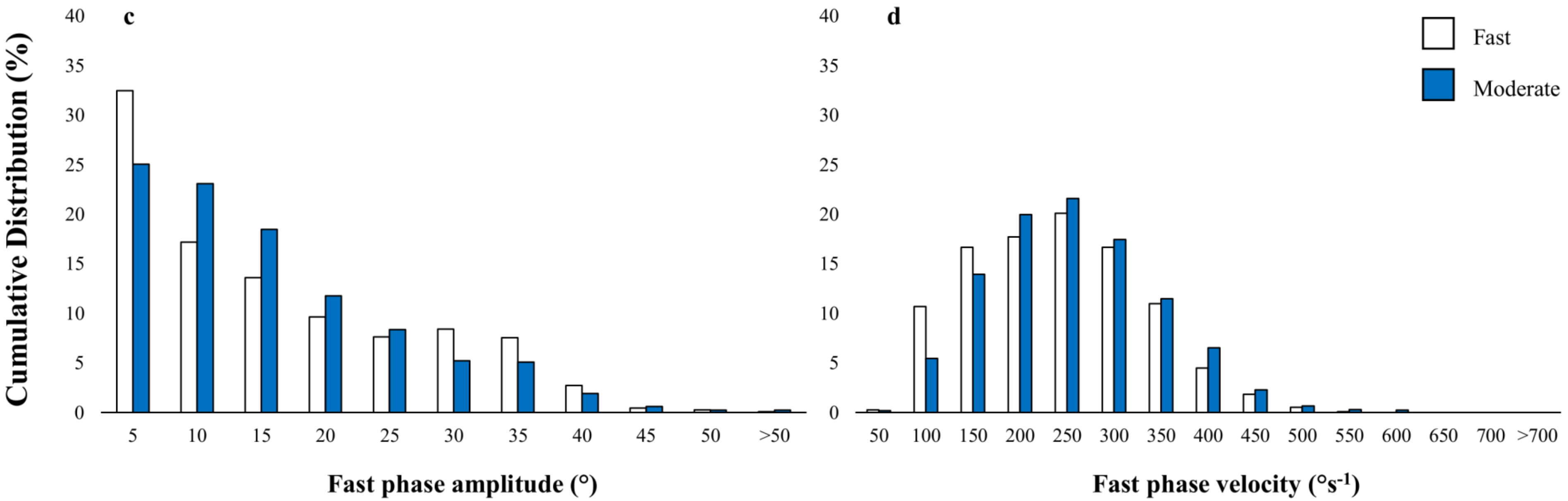

Figure 3-8c-d: Cumulative frequency distributions for each speed condition; a) the distribution of fast phase amplitude was positively skewed and showed that the vast majority of fast phases are 15° or smaller in amplitude. b) Fast phase velocity was normally distributed and showed that the mean fast phase velocity was around 250°s^{-1} in both fast and moderate speed conditions. K-S Z found no statistically significant differences between fast and moderate speed condition cumulative distributions of fast phase amplitude or fast phase velocity.

3.3.5 Stepping analysis

Total steps for each trial were counted and RM ANOVA found main effects of both turn speed ($F_{(1, 8)} = 11.72$, $P=.009$) and turn amplitude ($F_{(3, 24)} = 125.54$, $P<.001$). Post hoc analysis revealed that the number of steps increased significantly with all increases in turn amplitude in both speed conditions. However, there was only a significant effect of speed on 90° turns ($P=.004$). Correlation analysis between total steps and turn duration found a positive relationship ($R^2 = .46$, $P<.001$). Stepping frequency was calculated for each turn as the number of steps divided by stepping duration (i.e. onset time of leading step to the time of foot placement of the last step). Correlation analysis found there was no significant relationship between stepping frequency and peak head velocity ($P=.245$), but a strong negative relationship between stepping frequency and turn duration ($R^2 = .57$, $P<.001$). RM ANOVA revealed main effects of both turn speed ($F_{(1, 8)} = 27.66$, $P=.001$) and turn amplitude ($F_{(1.219, 9.752)} = 5.15$, $P=.042$) on stepping frequency. Post hoc pairwise comparisons found no significant differences in stepping frequency between the different turn amplitudes in either speed condition. Post hoc analysis found that stepping frequency significantly increased with increased turn speed in all turn amplitudes.

Step size was calculated for all steps (see section 2.4 Step Analysis); RM ANOVA was performed on the leading step size and the trailing step size. There were no main effects of turn speed on either leading foot or trailing foot step size. A main effect of amplitude was found on both the leading step size ($F_{(3, 24)} = 16.28$, $P<.001$) and the trailing step size ($F_{(3, 24)} = 417.06$, $P<.001$). An interaction of speed and amplitude was found on the trailing step size ($F_{(3, 24)} = 4.09$, $P=.018$). Post hoc analysis revealed that the size of leading steps during 45° fast turns was not significantly different from the size of leading steps to 90°, but were significantly smaller than leading steps in the other turn amplitudes, and leading steps to 45° were significantly smaller than leading step sizes to all other amplitudes during moderate speed turns (Figure 3-9a). The size of trailing step was significantly different between all turn amplitudes, but there were only significant differences due to speed in the 180° turns (P=.030) (Figure 3-9b).

Step duration was calculated for all steps as the interval between step onset and step placement time. RM ANOVA was performed on the leading step duration and the trailing step duration. A main effect of turn speed was found on the leading step duration ($F_{(1,\,8)} = 31.94$, $P<.001$) (Figure 3-10a) and trailing step duration ($F_{(1,\,8)} = 24.89$, $P<.001$) (Figure 3-10b). Post hoc analysis found significant differences between all turn amplitude pairs which showed that step duration significantly decreased in the moderate speed condition for both leading and trailing steps.

A main effect of turn amplitude was found on the trailing step duration ($F_{(3,\,24)} = 87.27$, $P<.001$). Post hoc analysis revealed that during fast speed turns, step duration was significant different between all turn amplitudes except between 135° and 180°. During moderate speed trials, trailing step duration was significantly shorter during 45° turns compared to all other turn amplitudes (Figure 3-10b).

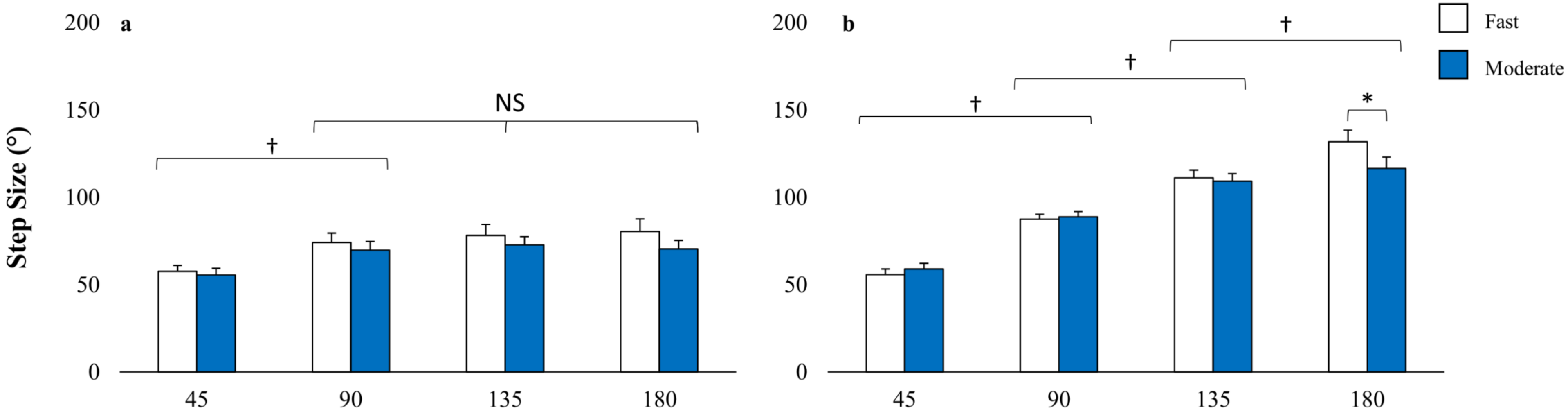

Figure 3-9: Mean step sizes for all experimental conditions; a) mean lead step size was significantly smaller during turns to 45° than to all other amplitudes for both fast and moderate speed turns. b) Mean trailing step size was statistically significant between all amplitudes, showing an increase in step size with increased amplitude. There were only statistically significant differences due to turn speed in the 180° turn condition which showed the trailing step was smaller during the moderate turns. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between speed conditions and brackets with daggers represent statistically significant differences between amplitude conditions.

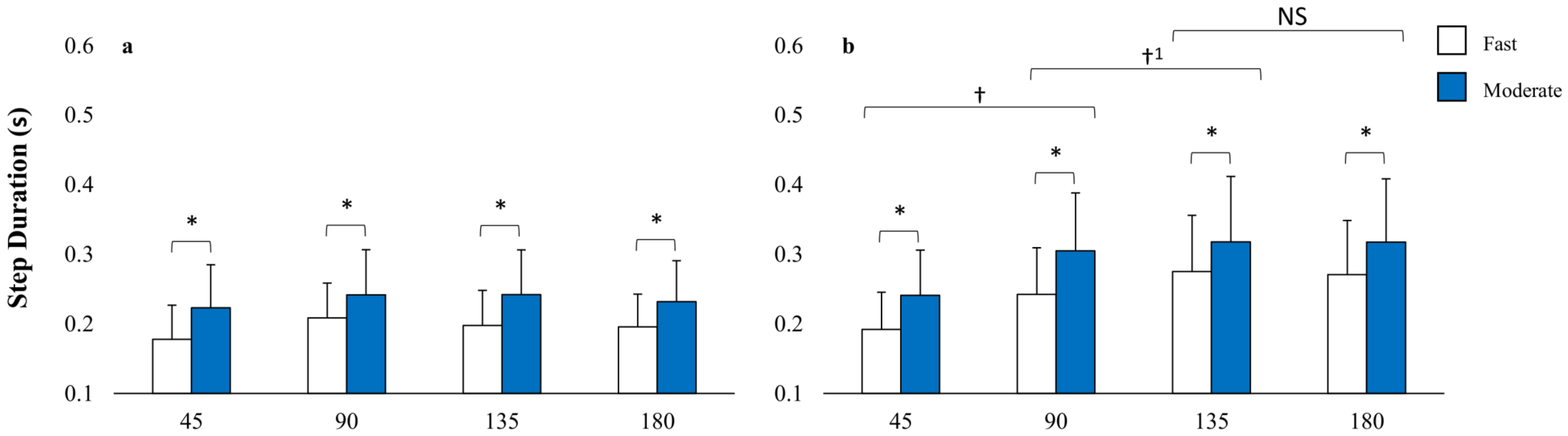

Figure 3-10: Mean durations for all experimental conditions; c) mean lead step duration was significantly longer during moderate speed turns than during fast turns for all turn amplitudes. There were no differences in lead step duration due to turn amplitude. b) Mean trailing step duration was significantly shorter during moderate speed turns than fast turns for all turn amplitudes. Mean trailing step duration was significantly shorter during turns to 45° than to all other turn amplitudes. [1]During fast speed turns only, trailing step duration was significantly shorter during 90° turns than during either 135° or 180° turns, which were not significantly different from one another. During moderate turns, mean trailing step size did not vary significantly between 90°, 135° or 180° turns. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between speed conditions and brackets with daggers represent statistically significant differences between amplitude conditions.

3.4 Discussion

The aim of this study was to explore the relationships between oculomotor behaviour and kinematics and how these relationships are altered by manipulating turn direction, turn amplitude and turn speed. We found that turn amplitude and turn speed systematically altered both eye movements and intersegmental movements during whole-body rotations. At the beginning of a turn, intended turn speed modulated the timing of turn onset i.e. for faster turns, turn onset occurred sooner than for slower turns. Throughout the turn, the degree of separation between the head and the lower segments or the ‘head anticipation’ increased with both increased turn amplitude and increased turn speed. Fast phase eye movements seen throughout the turn were related to the duration of the turn, i.e. larger turns elicited more fast phases and slower turns elicited more fast phases. The spatial characteristics of the fast phase, the amplitude and velocity, were larger and faster during faster turns. Stepping behaviour did not appear to follow that of the axial segments and eyes; step duration was only modulated by turn speed, that is slower turns had longer step duration, but increasing turn amplitude did not alter step duration. Additionally, step size only changed with increasing amplitude; steps did not become larger during faster turns.

3.4.1 Reorientation sequence

The order of reorientation of the segments occurred using a head-first strategy rather than the gaze-initiated steering strategy that has commonly been reported in the literature (Grasso *et al.*, 1998; Hollands, Sorensen and Patla, 2001; Hollands, Ziavra and Bronstein, 2004; Anastasopoulos *et al.*, 2009; Reed-Jones *et al.*, 2009a; 2009b; Degani *et al.*, 2010). One possible explanation is previous studies have used visual cues presented in the peripheral visual field which will have likely evoked an initial reflexive saccadic eye movement or have potentially evoked a visual search behaviour when the goal of the task is to align gaze with a particular position. Our current protocol was dependent on spatial memory rather than using ‘targeted’ turn locations, such as those seen in previous studies (Hollands, Ziavra and Bronstein, 2004; Anastasopoulos *et al.*, 2009; Hong, Perlmutter and Earhart, 2009; Degani *et al.*, 2010; Lohnes and Earhart, 2011; 2012; Ashburn *et al.*, 2014) and therefore it is perhaps unsurprising that the characteristic of the initial eye movement differed. A study performed by Ashburn *et al.* (2014) also found a head-first strategy in both healthy older adults and Parkinson’s patients, despite their protocol including an LED target; however, as the study was limited to 180° turns, the participants were not required to make turns to unpredictable locations. The predictability of the turn location may play a role in determining the timing characteristics (i.e. the sequence and intersegmental latencies) of segment reorientation. Anastasopoulos *et al.* (2009) showed that trials to predictable locations resulted in smaller differences between latencies of the different segments than turns of similar magnitude to unpredictable locations. Similarly, in the current study the differences between onset latencies for the eyes, head and body segments were generally small (less than 100ms difference between all axial segments) indicative of what has previously been described as *en bloc* movement (Lamontagne, Paquette and Fung, 2007; Lamontagne and Fung, 2009; Anastasopoulos *et al.*, 2009; Hong, Perlmutter and Earhart, 2009; Hollands *et al.*, 2010a, 2010b). However, as discussed in the following section, differences between the onset latency of segments do not necessarily represent what happens during the course of the turn and so additional measures are needed to fully describe turning behaviour. While onset latencies should not necessarily be used as dependent variables, onset latencies and rotation end times should be incorporated and the time normalised trajectories used for subsequent analysis.

3.4.2 Extent of *en bloc* behaviour predicted by turning speed

Although the similarities between mean onset latencies of the axial segments suggest the different upper body segments started to move in an *en bloc* manner (Figure 3-2[1]) it is clear when looking at the inter-segmental relationships, that increases in both the amplitude and speed of the turn significantly influence the extent to which the segments rotate relative to each other (Figure 3-4b), which has also been shown in curved path walking (Sreenivasa *et al.*, 2008). It is important to note that we found no significant relationship between differences in head and pelvis rotation onset latency and subsequent peak head-pelvis angular separation during the turn. We did find, however, a significant correlation between turn speed and maximum head-pelvis angular separation demonstrating that the extent to which the head leads the other segments is linearly related to, and can be predicted from turning speed. The y-intercept of the regression line suggests that the upper body moves in a truly *en bloc* manner (i.e. segments move together for the duration of the turn) only when peak head velocity is less than approximately 85°s^{-1}. Interestingly, we found that the peak velocity increased with increased turn amplitude, while the opposite occurs during turns while walking (Huxham *et al.*, 2008; Sreenivasa *et al.*, 2008). This is likely due to the postural demands of the task, as turns while walking progress the COM forward while the on-the-spot turns require the COM to remain balanced within a rotating BOS; while the two tasks may both elicit the reorienting synergy for initiation, they may be sufficiently different from one another to be controlled via different mechanisms.

Changes in spatial head anticipation or the amount of separation between the head and the trunk segments with concurrent changes in turn behaviour suggest that head anticipation may aid in providing the eyes with the most appropriate head-on-trunk position in order to gain advance visual information. That is, during larger turns, the head may rotate further away from the pelvis to obtain the image of the turn goal location prior to lower segment rotation. As the maximum amount of separation between the segments occurred approximately mid-way through the turn for all amplitudes and speeds, it may suggest that the necessary spatial information for subsequent movement is attained by this point in the movement and the remaining motion is directed towards the visually attained spatial reference of the goal which is fed-forward for ongoing control. To determine whether the peak yaw separation is indicative of goal-referenced information, it would be ideal to perform goal-less turns, i.e. have participants turn and cue them to stop at pseudo-random time points rather than spatial locations. If the separation is indeed to attain a reference of the goal, one would assume that when the goal is unknown, peak separation would be reached early to attain pertinent visual information and a maximally separated state would be maintained until the stop cue was given. Conversely, if peak head-pelvis separation is comparable in same speed full vision and no vision turns, then it is unlikely that head anticipation occurs in order to facilitate a preview of the turn destination.

3.4.3 Eye movement behaviour and vision

Eye movement characteristics were fairly stereotyped with consistent nystagmus, showing a reduced number of fast phases during fast turns compared to moderate turns and an increased number of fast phases with increased turn amplitude. This suggests that the number of fast phases elicited is directly related to the duration of the turn i.e.

faster (shorter) turns will elicit fewer fast phases than slower turns to the same amplitude. Additionally, turns of comparable speeds, but different amplitudes will elicit a different number of fast phases. This finding could explain the observations of Lohnes and Earhart (2012) who found a reduced number of fast phases in Parkinson's patients with subthalamic nucleus deep brain stimulation (DBS) implants in the on versus the off phase while turning. Patients turned faster in the DBS-on phase compared to the DBS-off phase and elicited fewer fast phases in the on phase. However, they found no enhancement of saccadic performance in the DBS-on phase during a seated saccade protocol; oculomotor performance changed only when the kinematic performance changed. While the authors concluded that improved kinematics and oculomotor performance were both directly due to DBS, our results would suggest that the differences found in nystagmus characteristics in the Lohnes study is likely a by-product of faster turning and that DBS likely works directly on the locomotor, but not the oculomotor centres in the brain. In addition to consistent temporal characteristics, the vast majority of the fast phases elicited had a small amplitude, which supports the observations of Bahill *et al.* (1975) who measured saccades evoked during natural locomotion and found that the vast majority of saccadic eye movements which occur during normal movement are 15° or smaller in amplitude. It would seem that a larger degree of eye eccentricity would be advantageous during a sustained rotation within the yaw plane to gain advance visual information, however, it has been proposed that gaze serves to encode visual orientation (Buisseret, 1995) and the coded visual direction may serve to direct movements of the lower limbs (Neggers and Bekkering, 2001).

Furthermore, analysis of the main sequence of each turn amplitude and turn speed revealed no significant differences between the fast phase amplitude-velocity relationships, providing further evidence that the same mechanism elicits fast phases during both slow and fast whole-body rotations. However, while the correlation coefficients for each main sequence were strong (between 0.58-.69), comparisons with previous studies generally revealed stronger relationships between saccade amplitude and saccade velocity (Bahill *et al.* 1975). Main sequence analysis has generally been applied to saccades which are elicited in head restrained conditions (Bahill *et al.* 1975; Sharpe *et al.* 1975; Kaminiarz *et al.*2009) and results have generally shown good predictably of saccade velocity from saccade amplitude. However, Freedman and Sparks (1997a;b) compared the main sequence for saccades elicited in rhesus monkeys in both head restrained and head unrestrained conditions and found that saccades elicited with the head free to move had less predictable velocity profiles than head restrained saccades. Collectively the results of Freedman and Sparks and the current dataset show that the main sequence relationship weakens with the addition of degrees of freedom during rotational movements.

Although we did not find that the eyes initiated reorientation, gaze consistently led the turn (see arrow Figure 3-1) and spent the majority of the turn in advance of the head and body rotation, suggesting that either visual information about environmental features or proprioceptive information from the extraocular muscles about gaze direction could be used to control the ongoing trajectory of the lower segments. Although we were unable to ascertain whether environmental features were being fixated during the slow phases, it is possible that short fixations on arbitrary environmental features could provide sufficient visual information for an updated reference frame which could be used for online turning control. However, this is unlikely to be the driving mechanism of anticipatory saccades as successful navigation of curved, circular and complex trajectories is possible in darkness and without practice (Takei *et al.*, 1997; Grasso *et al.*, 1998; Courtine and Schieppati, 2003a; Authié *et al.*, 2015). Ultimately, to assess the specific effect of visual input on the fast phases of nystagmus, oculomotor behaviour while turning should be assessed under both full vision and no vision conditions and also during fixed gaze conditions, both with and without available peripheral visual information. This is the focus of the next experimental section (Chapter 4).

It is also noteworthy that faster and larger turns were associated with larger initial fast phases which leads to question whether the initial eye movement and intended turn behaviour is pre-programmed. The initial saccade as a part of the pre-programmed turning synergy is supported by the results of Reed-Jones *et al.* (2009a; 2009b) and Ambati *et al.* (2013) which demonstrated that preventing eye movements during turning causes significant disruptions in the coordination of the axial segments at turn onset. However, these studies mainly focused on steering behaviour during visually elicited turns and the ‘real’ turns performed in the Ambati *et al.* (2013) study did not alter the parameters of the turn (i.e. all turns were to 90°), therefore the effects of altering turn behaviour cannot be examined. Another explanation is that alterations in fast phase characteristics are a result of altered afferent input which is integrated into the mechanism which drives fast phases. If afferent vestibular signals modulate fast phases, probing the effects of head acceleration on fast phase characteristics would be best suited to a passive rotation protocol, whereby the onset of acceleration as well as the acceleration curves could be highly controlled and the effects of head-on-trunk neck proprioceptive inputs, lower level proprioceptive inputs as well the release of the reorienting synergy itself could be eliminated. The effects of different rotation speeds on the main sequence of vestibular nystagmus induced by passive rotation in monkeys have shown that increased speeds had no effect on the main sequence relationship (Ron, Robinson and Skavenski, 1972). While there are differences eye movement characteristics between monkey and man, the results of the main sequence analysis for the current study support the notion that stimulation, i.e. rotation speed, does not affect main sequence characteristics. However, the study by Ron et al. did not look at the initial fast phase separately, so whether different spatial characteristics were present due to rotation speed in that specific fast phase is unclear.

The current body of passive rotation literature is largely focused on the VOR gain and incorporates sinusoidal rotation along with fixation, which is not suitable for comparison with the contributions of the VOR during natural whole-body rotation, however, Pulaski *et al.* (1981) did investigate eye movements during passive *en bloc* rotation of participants and found alterations in fast phase characteristics with changes in rotation speed, however they did not select the initial fast phase for individual analysis. Additionally, it is unclear if the chair rotation acceleration or velocity reflected natural head rotation and the rotation appeared to be continual, which may have led to a saturation effect whereby semi-circular canal input would have eventually been eliminated. However, by comparing active head-on-trunk rotations with passive *en bloc* rotation, the authors demonstrated that VOR gain remains closer to unity for a larger range of head velocities during active rotations, suggesting that neck proprioception may enhance gain properties during when actively maintaining gaze. Additionally, the study was performed in complete darkness, therefore comparisons were between purely vestibular nystagmus and nystagmus mediated by both vestibular proprioceptive input, while the current study was performed with full ambient lighting and thus including a visual component as well, which would likely mean that direct comparisons between results would still differ due to optokinetic input.

While the relative contributions of the sensory systems to nystagmus characteristics during active whole-body rotations is still relatively undefined, the contributions of the vestibular system to nystagmus characteristics during passive rotation have been extensively studies over the last half century. Studies using sinusoidal rotations have shown that the slow phase component of nystagmus compensates for head movements while the fast phase represents a resetting mechanism (Barnes, 1993). The slow phase has two main features, one is the gain, which is the ratio between the eye and head velocity, where unity, i.e. a gain of 1, represents perfect compensation and the phase relationship, which is the time lag between the head and eye movement, which is zero for perfect compensation. The time lag for the VOR is closer to 10 ms for all planes of movement (Aw *et al*. 1996). As stated previously, the gain of the VOR is higher during active head movements than during passive head movements (Barnes *et al.* 1985). Importantly, the VOR gain is maximal between frequencies of 0.5 Hz and 2 Hz (Barnes, 1979), which represent rotation velocities during normal human movement, however, during slow turns, such as those performed by patients with difficulty turning, VOR gain may not be sufficient for gaze stabilization, which means that slow turns, which may rely more heavily on visual and proprioceptive input, need to be studied to determine how gaze behaviour and gaze stability is maintained when the vestibular contribution is less than ideal. The fast phase component of nystagmus has been less thoroughly examined than the slow phase. Examination of nystagmus in the cat found that NFPF was no higher than 4 per sec (Donaghy 1980), which is in line with the NFPF found in this study which was usually between 2-3Hz (Table 3-2). The author reasoned that this apparent NFPF threshold was to allow adequate time for visual processing. If this is true, then NFPF would be expected to be different during rotations in darkness, when visual input would not be processed at all. This is discussed further in the next chapter.

3.4.5 Control of stepping movements

While we initially expected slower turns to be achieved via a larger quantity of smaller amplitude steps, as normally exhibited by slower turning clinical patients, we found that the participants actually decreased the frequency of their stepping, but the number of total steps remained relatively constant between conditions. Spatial differences between stepping strategies were observable from the initial step (Figure 3-9a) which show that steps to turn amplitudes above 45° were significantly larger than steps to 45° at around 75° in each amplitude and speed condition. The lack of differences in initial step size between the larger amplitude turns can likely be explained by biomechanical factors. The trailing step size increased significantly with each increase in turn amplitude (Figure 3-9b). Step placement during pre-planned turns could be part of either a planned mechanism or could be reactionary and dependent on visual perception of the surroundings. Analysis of stepping strategies during turns with full vision and no vision conditions to different turn amplitudes would be necessary to confirm this prediction. Step duration results were consistent between turn amplitudes and within each speed condition (Figure 3-10). It is likely that the temporal step pattern observed during turning is mediated via the central pattern generators (CPG) in the spinal cord which encode the rhythmic pattern used while walking (Duysens and Van de Crommert, 1998). It appears that during pre-planned turns, changes in turn speed are implemented by modulating the temporal stepping characteristics and changes in turn amplitude are achieved by changing the size of the steps, specifically at gait initiation. Given that stepping frequency is not altered between turn amplitudes, changes in step size must be implemented via an increase in step velocity.

Despite the changes in turn amplitude, we found that the size of the leading step remained relatively constant, however, the amplitude of the second (trailing) step increased as the intended turn amplitude increased. Our results are comparable with Vallabhajosula *et al.* (2013) who examined multi-directional gait initiation and found leading step durations were constant between the different directions; overall results showed that step length changed with step-direction, however their step protocol was limited to medial and lateral steps to 45° and lateral steps to 90°. Breniere and Do (1986) examined the gait initiation process during forward motion and found that the characteristics of the initiating step were constant despite changes in the intended walking velocity. It is more than likely that initiating forward translation will differ significantly from gait initiation during rotation and to fully interpret gait initiation during on-the-spot turns and the differences between the leading and trailing steps, displacement of the COM as well changes in the centre of pressure of each foot need to be taken into consideration, especially as changes in walking velocity have been shown to significantly alter both temporal and spatial plantar pressure characteristics (Taylor *et al.*, 2004). An additional confound is the limited number of steps taken by our participants, especially during smaller turns, meaning that a ‘steady-state’ gait- is never reached; the leading step initiates gait while the trailing step terminates gait.

3.5 Conclusion

Our results demonstrate systematic relationships between turning speed, eye movement and axial segmental coordination characteristics during standing turns. Importantly, the extent to which a turn is carried out in an *en bloc* manner is dependent on the turning speed, but not timing of initial axial segment rotation. Therefore the timing of segment reorientation should not be used as measure of intersegmental coordination. Stepping characteristics are highly consistent during turning but are relatively independent from changes in turn context. The role of gaze fixations during the slow phase of turning nystagmus is unclear but gaze fixations may act to facilitate dynamic head stabilization during locomotion.

Chapter 4

The effects of constraining vision and eye movements on whole-body coordination during standing turns

4.1 Introduction

During large whole-body turns, there is a characteristic pattern of eye movement behaviour called nystagmus which consists of alternating fast and slow movements away from and back towards the centre orbit. Following the fast eye movement into the turn direction, or fast phase, is a slow counter rotation of the eye, or slow phase, back towards the centre of the orbit, which is generated by the vestibulo-ocular reflex. The intermittent fast phases, also called anticipatory eye movements, along with the compensatory slow phases are made throughout the turn, until the completion of motion. Intuitively, one would assume that these anticipatory eye movements serve to obtain visual information about the upcoming spatial environment, however, anticipatory eye movements are observable even in darkness (Grasso *et al.*, 1998; Authié *et al.*, 2015). In fact, many studies which have analysed turns in darkness have shown comparable performance with normal vision turning (Takei, *et al.* 1997; Grasso *et al*, 1998; Courtine and Schieppati, 2003a). It has been suggested that eye-head coordination during steering contributes to trajectory planning as there is anticipatory top-down organization of the body (i.e. the eyes anticipate head and the head anticipates the body's trajectory) during complex curve walking (Bernardin *et al.*, 2011). Gaze location predicts the future trajectory of the lower segments in both time and space; increases in path curvature increase the time of anticipation. However, our previous study also demonstrated that turn speed has a significant influence on both anticipatory eye and head behaviour, even when turns were to the same amplitude i.e. the same trajectory. The conclusion was that greater anticipation was used to facilitate an earlier preview of the turn location. If anticipation is used for previewing, then eye (and head) movement behaviour should be substantially different between turns performed with visual input versus turns with vision removed.

The ability to move one's eyes during steering also appears to be necessary for coordinated movement. In a series of steering experiments, Reed-Jones and colleagues (2009a) showed that steering responses can be visually elicited via rotation of the external environment. While stepping-in-place, participants viewed a virtual scene of movement around a corner and significant eye and axial segment rotations were observed which were characteristic of steering in real world turning. Subsequently, the participants performed the same visually elicited steering protocol, but with a fixed gaze condition which prevented participants from making any eye movements. The fixed gaze condition suppressed the anticipatory steering responses (Reed-Jones *et al.*, 2009b). Translating this paradigm to real-world steering, the participants were asked to walk towards a wall and make a 90° turn under free gaze and fixed gaze conditions (Ambati *et al.*, 2013). 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, but did not force the participants to make counter rotations of the eye throughout the remainder of the turn. The authors found that gaze fixation, specifically during turn initiation caused a disruption in the sequence of reorientation and that turns were initiated *en bloc*. However, as our previous study demonstrated, a saccade is not necessary to initiate turning, so are fast phases necessary throughout turning? And if so, what purpose do they serve? Additionally, there are many neurological populations who have both difficulty turning and deficits in oculomotor control such as Parkinson's, cerebellar and stroke patients, which frequently manifest as delays in gait initiation and inappropriate or inadequate stepping behaviour, so are the fast phases generated during turning necessary to control stepping behaviour?

The main objective of the current study was to elucidate the relative contributions of vision and eye movements to whole-body coordination during standing turns by observing the effects of separately removing vision and preventing eye movements. We predicted that the constrained eye movement condition would disrupt motor coordination, whereas vision removal would have little effect on coordination. Secondary aims were to a) compare eye movement control with and without vision to clarify the role of eye movements during turning and b) observe the effect of vision removal and eye movement constraint on stepping characteristics during turns. We predicted that i) eye movements would be comparable in both vision and no vision conditions and ii) removal of vision would not alter step characteristics, but fixating gaze would alter stepping behaviour.

4.2 Methods

4.2.1 Participants

Seventeen healthy young adults (mean age 24.92 ± 3.00 *SD*) volunteered for the study. The experimental protocol was approved by the Liverpool John Moores Research Ethics committee (REC) and all participants gave written and informed consent. Participants were excluded if they reported neurological, musculoskeletal, or cognitive impairments, or if they were taking medication for anxiety and/or dizziness or used an assistive walking device. All participants had normal or corrected to normal visual acuity (20/20 or better).

4.2.2 Protocol

The trials were arranged in three blocks: full vision (FV), no vision (NV) and gaze fixation (GF) conditions. Other experimental conditions included turn direction (left or right) and turn amplitude (90° or 180°). The FV condition was performed free from any eyewear (unless the participant wore corrective lenses) or headgear and allowed the participant full visual information at all times. The NV condition was performed using PLATO visual occlusion spectacles (Translucent Technologies, Toronto, Canada). Fabric was used to surround the frames in order to remove any peripheral vision, which permitted the participant to perform the turns with eyes open, but without any visual information about environmental features. The GF condition was performed using a device which allowed free movement of the head from the neck with a fixed point in the line of sight approximately 35 centimetres away from the participant's head which rotated with the participant during the turn (Figure 4-1). The participants were instructed to maintain their gaze on this fixation point throughout the course of each fixation trial. All laboratory lights remained lit throughout the session. Counter-balancing measures were taken to account for the potentially confounding effect of block order, resulting in six blocks with three participants each. Trial order within each block was fully randomised for each participant. A total of 5 trials were recorded for each condition for a total of 60 trials. Prior to the experimental trials, the turn speed acquisition phase described in Chapter 2 was performed to acclimatise participants to the desired turn speed for all the trials.

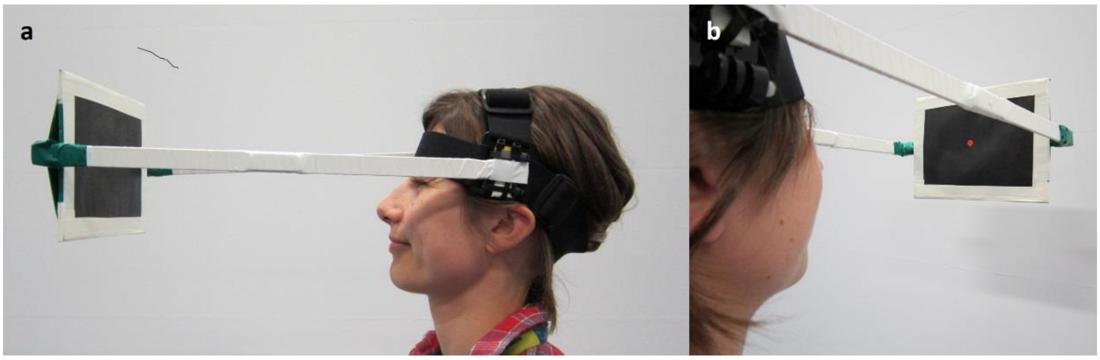

Figure 4-1: a) Head-mounted device used during the GF block which allowed free head-on-trunk rotation b) A small dot was placed in the centre of the board on the head-mounted device which was used as the fixation point during the trials.

4.2.4 Data analysis

Fixation trials. Trials performed within the fixation block were visually inspected for protocol adherence using both eye and gaze profiles and were excluded if any vestibular-mediated nystagmus or saccades which exceeded fast phase amplitude criteria (≥1.5°) were elicited.

4.2.5 Statistical analysis

The statistical package SPSS (22.0) was used for all statistical procedures. A 2 x 2 x 3 RM ANOVA was performed on all kinematic dependent variables with direction (left or right), amplitude (90° or 180°) and visual condition (FV, NV or GF) as repeated measure factors. As fixation trials elicited no fast phases, a 2 x 2 x 2 RM ANOVA was performed on all fast phase dependent variables, which included only vision and no vision data. No effects of turn direction (left versus right) were found; therefore the presented results are from 2 x 3 and 2 x 2 RM ANOVA design for the kinematic and EOG data, respectively. RM ANCOVA was subsequently performed on significant results to control for turn speed using peak head velocity as a time-varying covariate. Pearson’s Product moment correlation was used to determine the strength of the relationships between the dependent variables. Main sequence analysis was performed on fast phase data for all experimental conditions; correlation coefficients were then compared using a Fisher transformation. Frequency distribution analysis was performed on all fast phase characteristics and Kolmogorov-Smirnov Z was run to determine differences between the distributions from each experimental condition. All mean values are presented with standard deviations unless otherwise stated. Statistical significance was set at $P<.05$. A Bonferroni's correction was used for multiple comparisons.

4.3 Results

Figure 4-2 shows displacement curves for all segments during all three visual conditions which shows that nystagmus was still elicited during the NV condition (Figure 4-2b), however, during the GF condition (Figure 4-2c), nystagmus was effectively abolished. Small movements of the eyes still occurred, but any trial with eye movement which fit the criteria used to determine a fast phase was removed from the analysis.

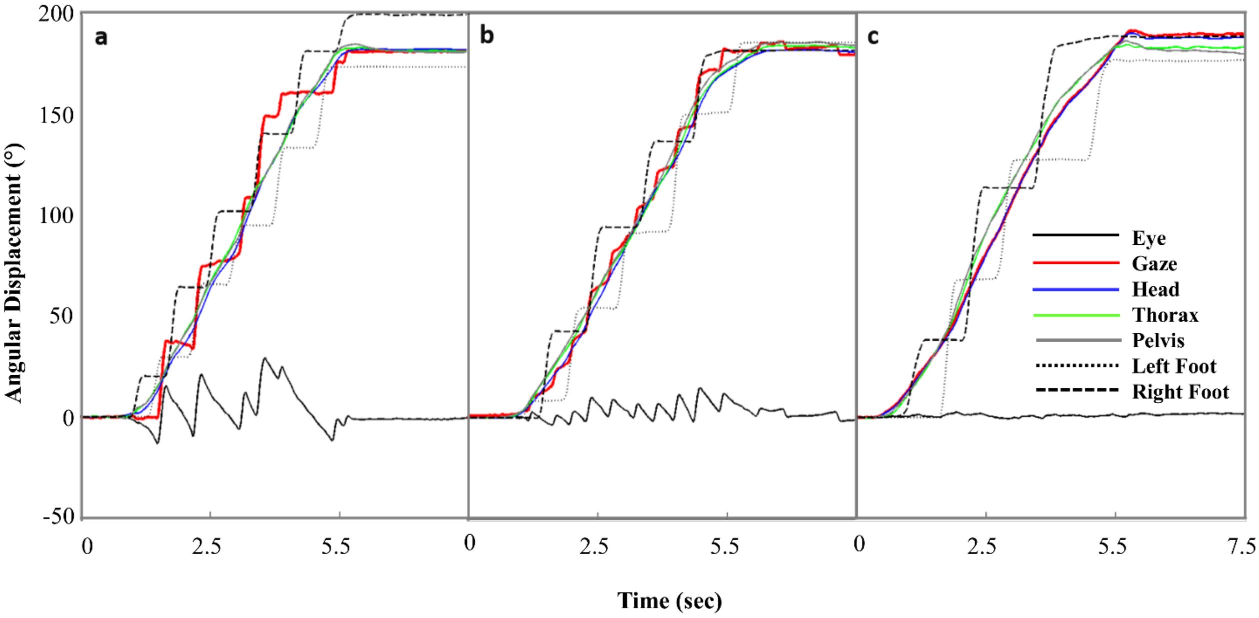

Figure 4-2: Displacements for all segments, including gaze (i.e. eye+head) showing turns during a) full vision, b) no vision, due to occlusion from PLATO goggles and c) gaze fixation which effectively suppressed the characteristic fast and slow phases of nystagmus. All trials found to have any eye movement similar to a fast phase or a saccade were removed from the dataset.

4.3.1 Segment onset latencies

The order of segment reorientation began with the axial segments, followed by the rotation of the eyes and then the onset of the leading and trailing feet (Figure 4-3), however, the exact order of onset of the axial segment rotations was inconsistent between the experimental conditions (Table 4-1). There was a main effect of turn amplitude on the rotation onset latencies for the head: $F_{(1, 16)} = 6.30$, $P=.023$; thorax: $F_{(1, 16)} = 4.83$, $P=.043$; pelvis: $F_{(1,16)} = 6.24$, $P=.024$; leading foot: $F_{(1, 16)} = 10.91$, $P=.004$; and trailing foot: $F_{(1, 16)} = 20.52$, $P<.001$), which showed that the onset latencies during the 180° turns were earlier than for the 90° turns for all visual conditions. There was no main effect of turn amplitude on the onset latency of the eye.

There was a significant main effect of visual condition on the onset latencies of the leading step ($F_{(2, 32)} = 22.17$, $P<.001$) and the trailing step ($F_{(2, 32)} = 19.49$, $P<.001$); pairwise comparisons revealed that the onset latencies of both the leading and trailing feet in the GF condition were significantly later ($P<.001$) than the onset latencies in the FV and NV conditions (Figure 4-3). Mean data showed that the onset latency of the leading step was approximately 120ms later and the onset latency of the trailing step was 200-300ms later in the GF condition compared to the FV and NV conditions (Table 4-1). Pearson’s product moment correlation analysis revealed significant correlations between the onset latencies of all segments (Table 4-1).

To determine whether differences found between leading and trailing foot onset latencies were potentially due to differences in turn speed, RM ANCOVA was performed using peak head velocity as a time-varying covariate. However, the effects of gaze fixation were preserved, demonstrating that turning speed cannot explain the effect. Additionally, Pearson correlation was performed between peak head velocity and the onset latencies of each foot for each of the visual conditions separately. Significant, but weak relationships were found between peak head velocity and leading step onset in the GF ($R^2 = .02$, $P=.018$) condition and between peak head velocity and trailing step onset in the FV ($R^2 = .03$, $P=.001$) and GF ($R^2 = .12$, $P<.001$.) conditions.

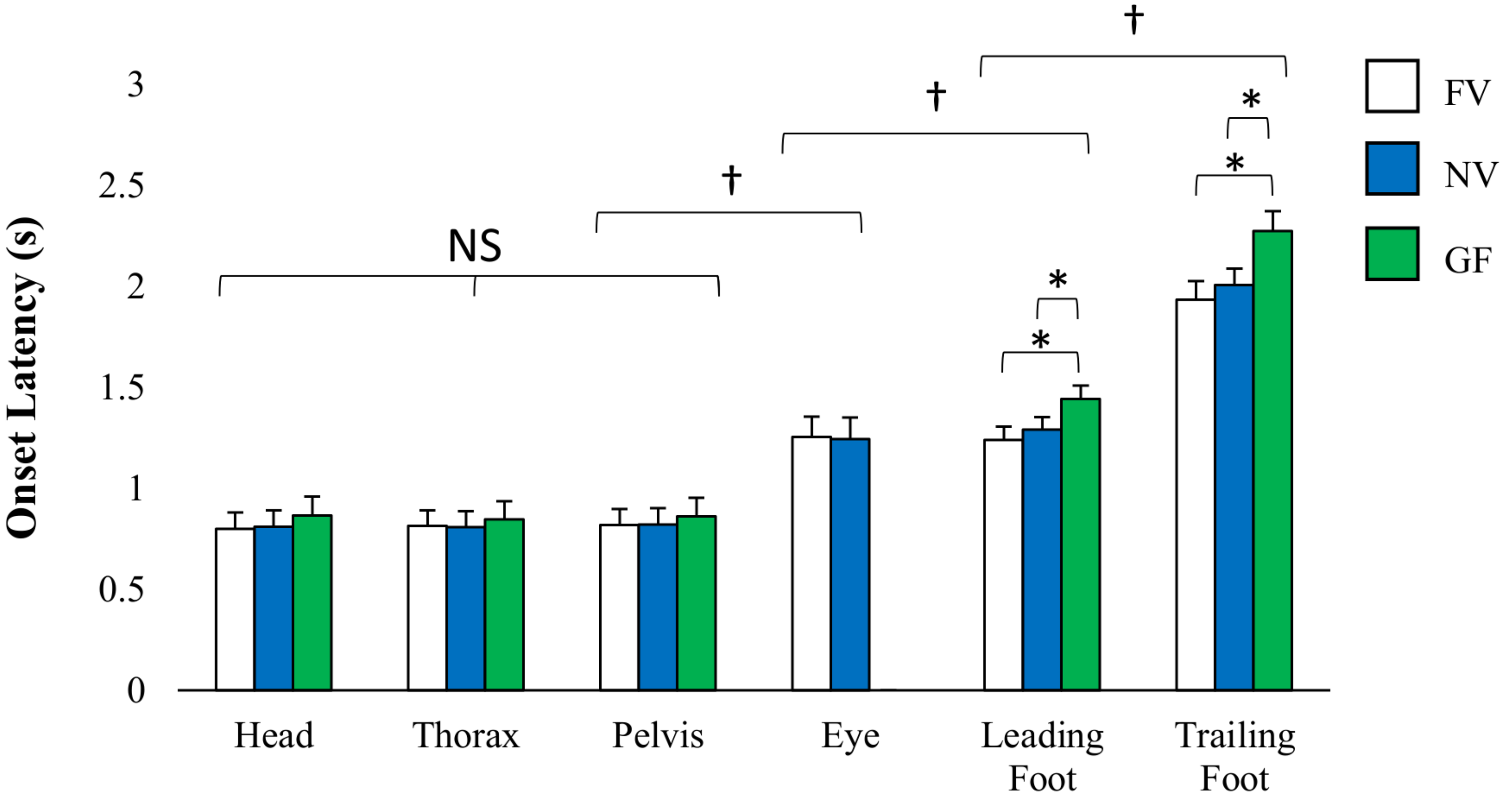

Figure 4-3: Mean onset latencies with amplitudes collapsed for all segments. Significant differences due to visual condition were found in the onsets of the leading and trailing feet which showed delays during GF. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between visual conditions and brackets with daggers represent statistically significant differences between segments.

Table 4-1a

Mean onset latencies (ms) for the FV trials for both turn amplitudes and the coefficient of determination (R^2) from Pearson's product moment correlations between the onset latencies of the eye, axial body segments and foot rotations from all participants during FV trials.

	90	**180**		**Eye**	**Head**	**Thorax**	**Pelvis**	**Leading Foot**	**Trailing Foot**
Eye	1262 ± 502	1249 ± 430	Pearson correlation		0.42	0.42	0.37	0.43	0.32
			Sig. (2-tailed)		<.001	<.001	<.001	<.001	<.001
Head	802 ± 386	773 ± 381	Pearson correlation	0.42		0.88	0.81	0.60	0.34
			Sig. (2-tailed)	<.001		<.001	<.001	<.001	<.001
Thorax	810 ± 370	811 ± 365	Pearson correlation	0.42	0.88		0.86	0.66	0.39
			Sig. (2-tailed)	<.001	<.001		<.001	<.001	<.001
Pelvis	826 ± 369	804 ± 382	Pearson correlation	0.37	0.81	0.86		0.61	0.37
			Sig. (2-tailed)	<.001	<.001	<.001		<.001	<.001
Leading Foot	1253 ± 296	1225 ± 334	Pearson correlation	0.43	0.60	0.66	0.61		0.80
			Sig. (2-tailed)	<.001	<.001	<.001	<.001		<.001
Trailing Foot	1968 ± 419	1900 ± 435	Pearson correlation	0.32	0.34	0.39	0.37	0.80	
			Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	

N = 330

Table 4-1b

Mean onset latencies (ms) for the NV trials for both turn amplitudes and the coefficient of determination (R^2) from Pearson's product moment correlations between the onset latencies of the eye, axial body segments and foot rotations from all participants during NV trials.

	90	**180**		**Eye**	**Head**	**Thorax**	**Pelvis**	**Leading Foot**	**Trailing Foot**
Eye	1291 ± 537	1196 ± 499	Pearson correlation		0.47	0.47	0.46	0.34	0.16
			Sig. (2-tailed)		<.001	<.001	<.001	<.001	<.001
Head	842 ± 387	769 ± 366	Pearson correlation	0.47		0.86	0.67	0.55	0.04
			Sig. (2-tailed)	<.001		<.001	<.001	<.001	<.001
Thorax	827 ± 370	782 ± 369	Pearson correlation	0.47	0.86		0.89	0.61	0.05
			Sig. (2-tailed)	<.001	<.001		<.001	<.001	<.001
Pelvis	843 ± 383	794 ± 383	Pearson correlation	0.46	0.67	0.89		0.51	0.24
			Sig. (2-tailed)	<.001	<.001	<.001		<.001	<.001
Leading Foot	1312 ± 291	1271 ± 282	Pearson correlation	0.34	0.55	0.61	0.51		0.68
			Sig. (2-tailed)	<.001	<.001	<.001	<.001		<.001
Trailing Foot	2054 ± 400	1960 ± 343	Pearson correlation	0.16	0.04	0.05	0.24	0.68	
			Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	

N = 318

Table 4-1c

Mean onset latencies (ms) for the GF trials for both turn amplitudes and the coefficient of determination (R^2) from Pearson's product moment correlations between the onset latencies of the eye, axial body segments and foot rotations from all participants during GF trials.

	90	180		Eye	Head	Thorax	Pelvis	Leading Foot	Trailing Foot
Eye	*n/a*	*n/a*	Pearson correlation		*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
			Sig. (2-tailed)						
Head	895 ± 468	822 ± 408	Pearson correlation	*n/a*		0.86	0.82	0.44	0.13
			Sig. (2-tailed)			<.001	<.001	<.001	<.001
Thorax	876 ± 454	791 ± 380	Pearson correlation	*n/a*	0.86		0.87	0.54	0.18
			Sig. (2-tailed)		<.001		<.001	<.001	<.001
Pelvis	887 ± 455	818 ± 401	Pearson correlation	*n/a*	0.82	0.87		0.57	0.21
			Sig. (2-tailed)		<.001	<.001		<.001	<.001
Leading Foot	1478 ± 336	1406 ± 267	Pearson correlation	*n/a*	0.44	0.54	0.57		0.56
			Sig. (2-tailed)		<.001	<.001	<.001		<.001
Trailing Foot	2330 ± 507	2215 ± 404	Pearson correlation	*n/a*	0.13	0.18	0.21	0.56	
			Sig. (2-tailed)		<.001	<.001	<.001	<.001	

N = 298

4.3.2 Intersegmental relationships

RM ANOVA was performed on peak angular segment separation and a main effect of amplitude was found on the peak head-thorax separation ($F_{(1, 16)} = 33.47$, $P<.001$) and peak head-pelvis separation ($F_{(1, 16)} = 18.93$, $P<.001$), but not on the peak thorax-pelvis separation. Main effects of visual condition were found on the peak head-thorax separation ($F_{(1.149, 18.390)} = 6.32$, $P=.005$) and peak head-pelvis separation ($F_{(1.206, 19.192)} = 6.17$, $P=.005$) (Table 4-2). No interactions were found between turn amplitude and visual condition. RM ANCOVA was performed to determine if the differences between the conditions in peak head-thorax and peak head-pelvis were due to turn speed, however, the effects of gaze fixation were preserved, demonstrating that turning speed cannot explain the effect.

Table 4-2

Peak angular separations between the axial segments.

		Full Vision	No Vision	Gaze Fixation
Peak Head-Thorax Separation (°)	90°	7.83 ± 9.08	4.65 ± 4.23	4.34 ± 3.61
	180°	10.68 ± 7.95	6.86 ± 4.38	5.77 ± 4.34
Peak Head-Pelvis Separation (°)	90°	9.81 ± 9.86	6.12 ± 4.78	6.26 ± 4.35
	180°	12.38 ± 9.19	7.93 ± 5.21	7.29 ± 5.41
Peak Thorax-Pelvis Separation (°)	90°	3.88 ± 1.22	3.09 ± 0.99	3.41 ± 1.26
	180°	3.90 ± 1.45	3.25 ± 0.83	3.35 ± 1.41

Pearson correlation analysis between peak head yaw velocity and peak angular separation between the head and pelvis revealed a significant relationship ($R^2 = .13$, $P <.001$). As turn speed was found to vary significantly, separate correlations were performed for each visual condition. Similar relationships were found between peak head yaw velocity and peak head-pelvis separation in FV ($R^2 = .17$, $P<.001$) and NV condition ($R^2 = .17$, $P<.001$), however the relationship essentially disappeared in the GF condition ($R^2 = .05$, $P<.001$) (Figure 4-4).

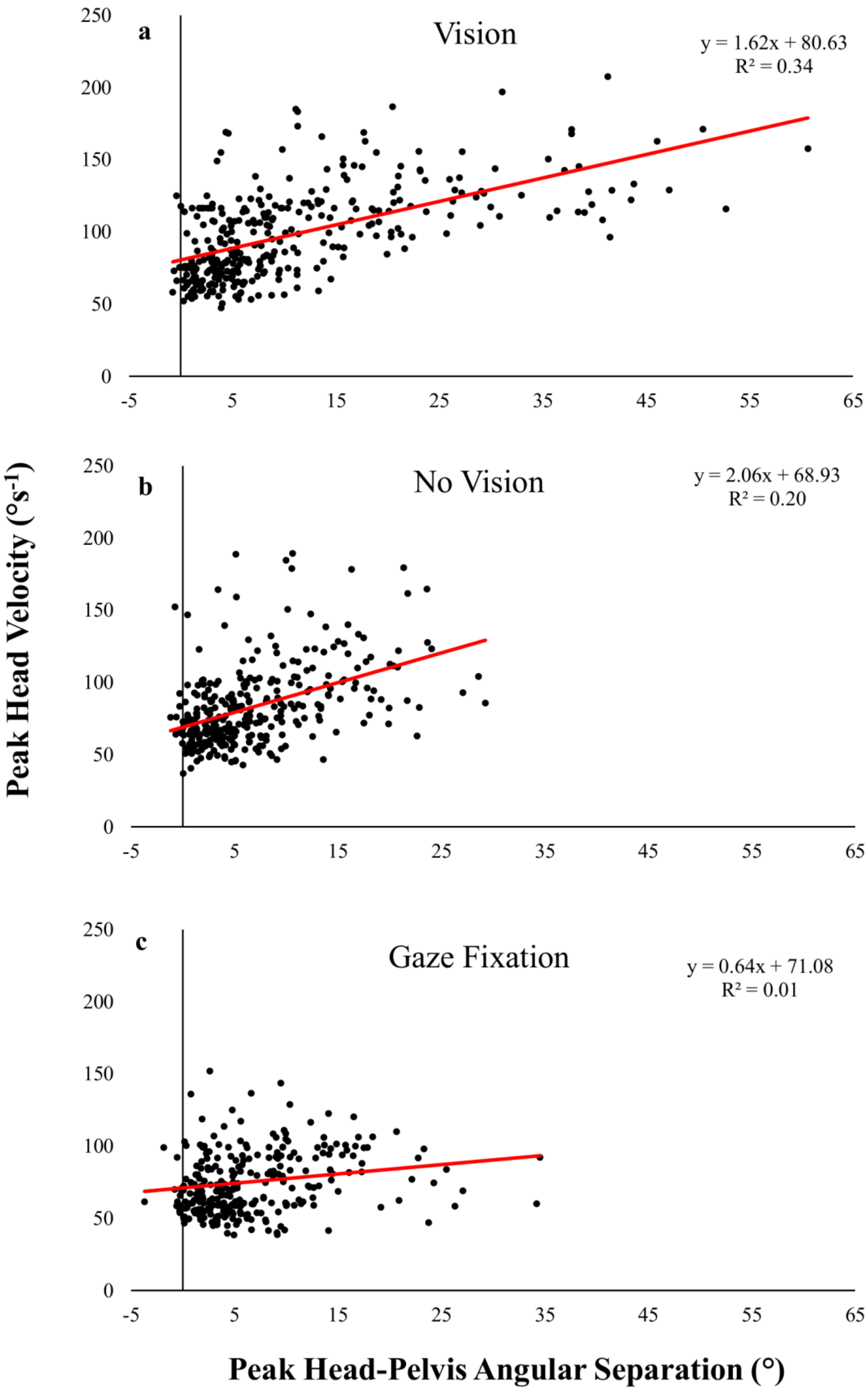

Figure 4-4: Peak head velocity accounted for approximately a third of the variability in peak head-pelvis separation during a) full vision and approximately a fifth of the variability during (b) no vision. The relationship between peak head velocity and peak head-pelvis angular separation effectively disappears when eye movements are suppressed in gaze fixation (c).

4.3.3 Fast phase characteristics

Significant differences were found in both the initial fast phase and maximum fast phase characteristics due to removal of vision. The initial fast phase amplitude was significantly larger ($F_{(2,\ 32)} = 37.32$, $P<.001$) and the initial fast phase velocity was significantly faster ($F_{(2,\ 32)} = 23.45$, $P<.001$) in the FV condition compared to the NV condition (Table 4-3). The maximum fast phase amplitude was significantly larger ($F_{(2,32)} = 64.86$, $P<.001$) and the peak fast phase velocity was significantly faster ($F_{(2,\ 32)} = 74.03$, $P<.001$) in the FV condition compared to the NV condition, however there were no main effects of vision removal on the acceleration characteristics of either the initial or peak fast phase.

Table 4-3

Mean and standard deviations for fast phase characteristics.

		Full Vision	No Vision
Initial Fast Phase Amplitude (°)	90°	20.04 ± 14.81	9.71 ± 8.20
	180°	19.91 ± 14.58	9.37 ± 7.27
Maximum Fast Phase Amplitude (°)	90°	28.01 ± 7.49	14.94 ± 7.18
	180°	30.14 ± 10.81	17.84 ± 6.76
Initial Fast Phase Velocity (°s^{-1})	90°	253. 30 ± 89.84	187.22 ± 62.73
	180°	253.47 ± 94.59	194.04 ± 76.26
Peak Fast Phase Velocity (°s^{-1})	90°	337.94 ± 65.40	249.31 ± 66.86
	180°	377.09 ± 76.55	289.11 ± 79.99
Initial Fast Phase Acceleration (°s^{-2})	90°	23484.33 ± 12007.00	22559.05 ± 9946.40
	180°	22208.91 ± 10887.07	23732.36 ± 11134.25
Peak Fast Phase Acceleration (°s^{-2})	90°	18945.03 ± 11212.04	29314.34 ± 10425.55
	180°	31661.97 ± 10938.72	34627.84 ± 18009.90
Number of Fast Phases (N)	90°	4.13 ± 1.87	4.96 ± 1.74
	180°	8.02 ± 2.87	8.51 ± 2.73
Nystagmus Fast Phase Frequency (Hz)	90°	1.97 ± 0.77	2.10 ± 0.72
	180°	2.35 ± 0.65	2.18 ± 0.66

Figure 4-5 shows the main sequence analysis of maximum fast phase amplitude versus peak fast phase velocity for both FV and NV conditions. Fisher transformation found that the correlation coefficients between FV and NV were significantly different (*P*<.001).

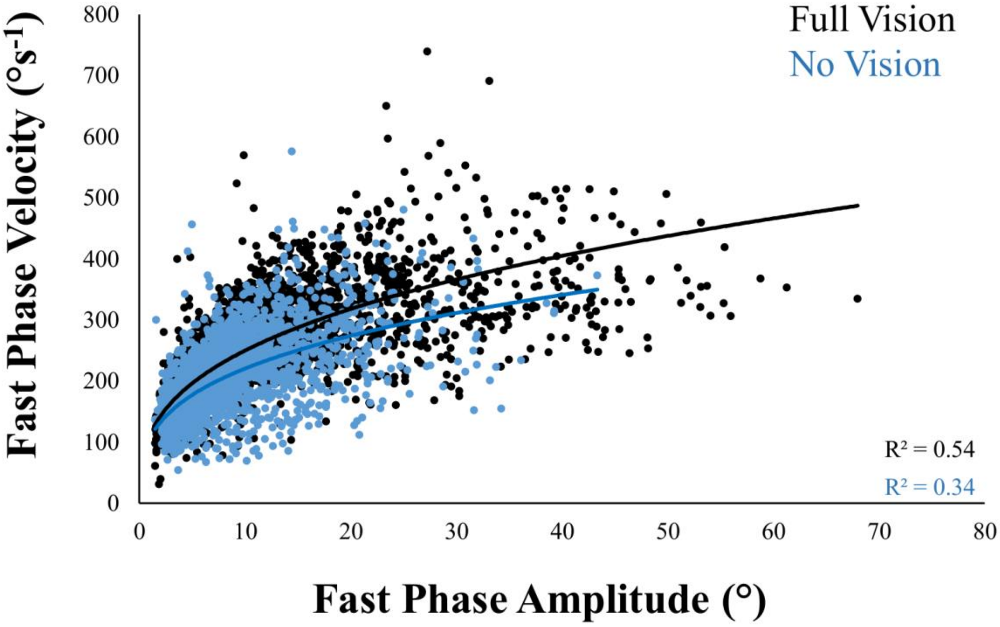

Figure 4-5: Man sequence plots for fast phases in FV and NV. The relationship between fast phase amplitude and fast phase velocity fit the main sequence law significantly more for fast phase elicited in vision.

There was no main effect of vision on the nystagmus fast phase frequency, however there was a main effect of turn amplitude on NFPF ($F_{(1, 16)} = 24.11$, $P<.001$) (Table 4-3) and an interaction between turn amplitude and visual condition ($F_{(1, 16)} = 8.44$, $P=.01$) which showed that the NFPF was significantly lower during 90° turns in FV than 180° turns during FV ($P<.001$) but there were no significant differences in NFPF between the turn amplitudes during the NV condition, nor were there any significant differences due to the visual condition (Figure 4-6).

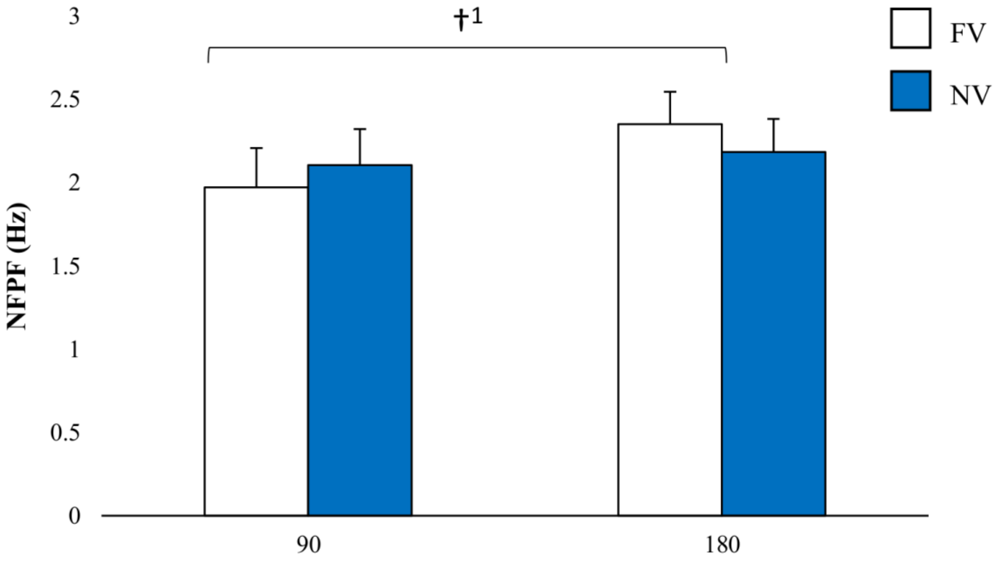

Figure 4-6: Nystagmus fast phase frequency was significantly higher during 180° turns than during 90° turns during trials with vision, however, ^{1}there was no difference in NFPF between amplitudes during no vision trials. Error bars represent 95% confidence intervals, brackets with daggers represent statistically significant differences between turn amplitude.

Pearson correlation analysis was performed between peak head velocity and the initial and peak fast phase characteristics. Significant relationships were found for the initial fast phase amplitude (R^2 = .16, P<.001), maximum fast phase amplitude (R^2 = .22, P<.001), initial fast phase velocity (R^2 = .04, P<.001) and peak fast phase velocity (R^2 = .03, P<.001).

Frequency distribution analysis was performed on the eye-in-orbit position at the beginning and end of each fast phase. While the majority of fast phases were elicited between -5° to +5° from primary position in both FV and NV conditions, fast phases elicited in the NV condition were generally closer to primary position, with only 2% of fast phases elicited from greater than +15° compared with 15% of fast phases in the FV condition (Figure 4-7a). The eye-in-orbit position continued to be more centrally located in the NV condition at the end of the fast phases, with approximately 79% being rotated 15° or less away from primary position compared to only 44% in the FV condition (Figure 4-7b). Frequency analysis on fast phase amplitude found a positively skewed distribution for both FV and NV fast phases, whereby approximately 66% of fast phases elicited in vision and approximately 87% of fast phases in no vision were 15° or smaller and (Figure 4-7c). Analysis of fast phase velocity found a normal distribution for both FV and NV conditions, however the mean velocity for fast phases in the NV was slower, between 200-250°s^{-1} than in the FV condition, where the mean fast phase velocity was around 300°s^{-1} (Figure 4-7d). Kolmogorov-Smirnov Z tests found no significant differences between any of the fast phase distributions.

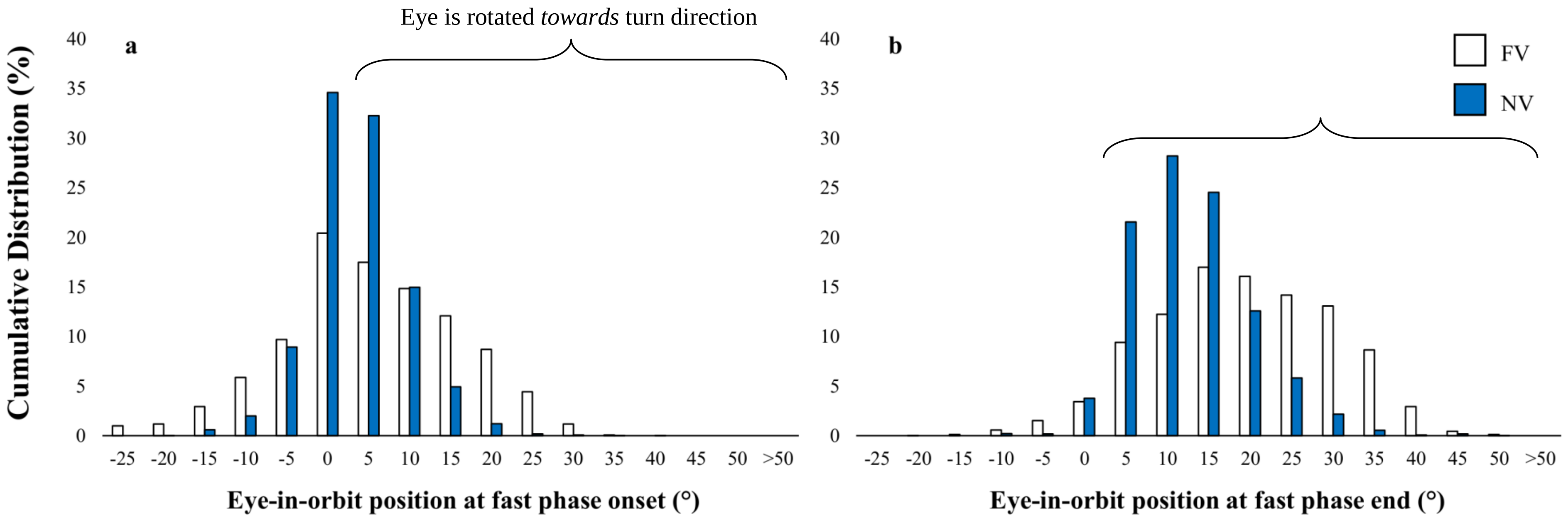

Figure 4-7a-b: Cumulative frequency distributions for FV and NV conditions. a) Distribution of eye-in-orbit positions at the onset of each fast phase showed that majority of fast phases were elicited from at or near the central orbital position (0°). b) Distribution of eye-in-orbit position at the end of each fast phase which show that the eye-in-orbit positions during FV are more eccentric than during NV. However, K-S Z found no statistically significant differences between FV and NV condition cumulative distributions of fast phase eye-in-orbit positions at either fast phase onset or fast phase end.

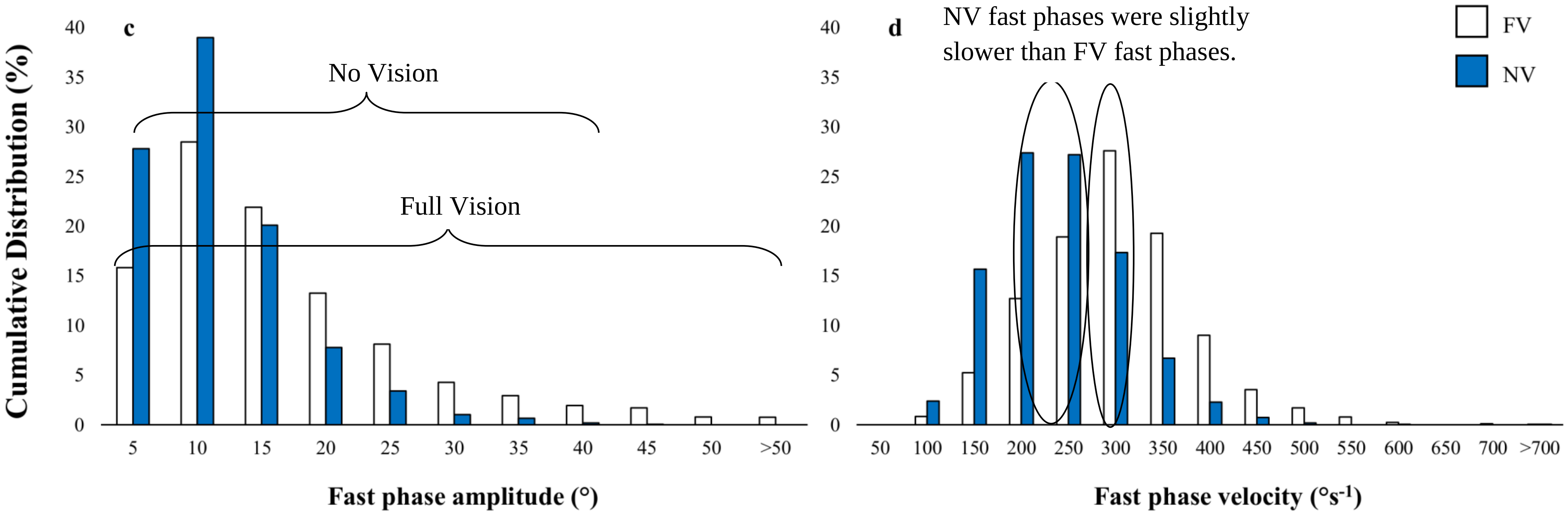

Figure 4-7c-d: Cumulative frequency distributions for FV and NV conditions. a) The distribution of fast phase amplitudes was positively skewed during both conditions and showed that the vast majority of fast phases are 15° or smaller in amplitude. b) Fast phase velocity was normally distributed and showed that the mean fast phase velocity was around 200-250°s^{-1} during NV and slightly faster in FV around 300°s^{-1}. K-S Z found no statistically significant differences between fast and moderate speed condition cumulative distributions of fast phase amplitude or fast phase velocity.

4.3.4 Stepping characteristics

RM ANOVA was performed on the leading step size and the trailing step size. A main effect of turn amplitude was found on both the leading step size ($F_{(1, 16)} = 4.48$, P=.01) and the trailing step size ($F_{(1, 16)} = 17.67$, P=.001). A main effect of visual condition was also found on both the leading step size ($F_{(2, 32)} = 3.46$, P=.044) and the trailing step size ($F_{(2, 32)} = 4.10$, P=.026). An interaction between turn amplitude and visual condition was found on only the leading step size ($F_{(2, 32)} = 6.78$, P=.004). Post hoc analysis revealed that the size of leading steps were significantly larger during 180° turns in the FV (P=.039) and GF (P<.001) conditions, but did not differ between amplitudes in the NV condition. Leading step size in the NV condition was significantly smaller than in both FV (P=.010) and GF (P=.009) conditions during 180° (Figure 4-8a). Trailing step size was significantly larger during 180° turns in all visual conditions. Trailing step size did not differ between visual conditions during 90° turns, but was significantly smaller during 180° turns in the NV condition than FV (P=.036), but did not differ significantly from GF (Figure 4-8b).

Step duration was calculated for all steps as the interval between step onset and step placement time. RM ANOVA was performed on the leading step duration and the trailing step duration. A main effect of turn amplitude was found on the trailing step duration ($F_{(1, 16)} = 6.22$, P=.024) (Figure 4-9b). A main effect of visual condition was also found on both the leading step duration ($F_{(2, 32)} = 3.40$, P=.046) and the trailing step duration ($F_{(2, 32)} = 4.65$, P=.017). No interactions were found between turn amplitude and visual condition. Post hoc analysis found that leading steps and trailing steps were significantly longer in 180° turns during GF than NV (leading: P=.016; trailing: P=.033) (Figure 4-9). Trailing steps were significantly longer to 180° than 90° during FV only (P=.002) (Figure 4-9b).

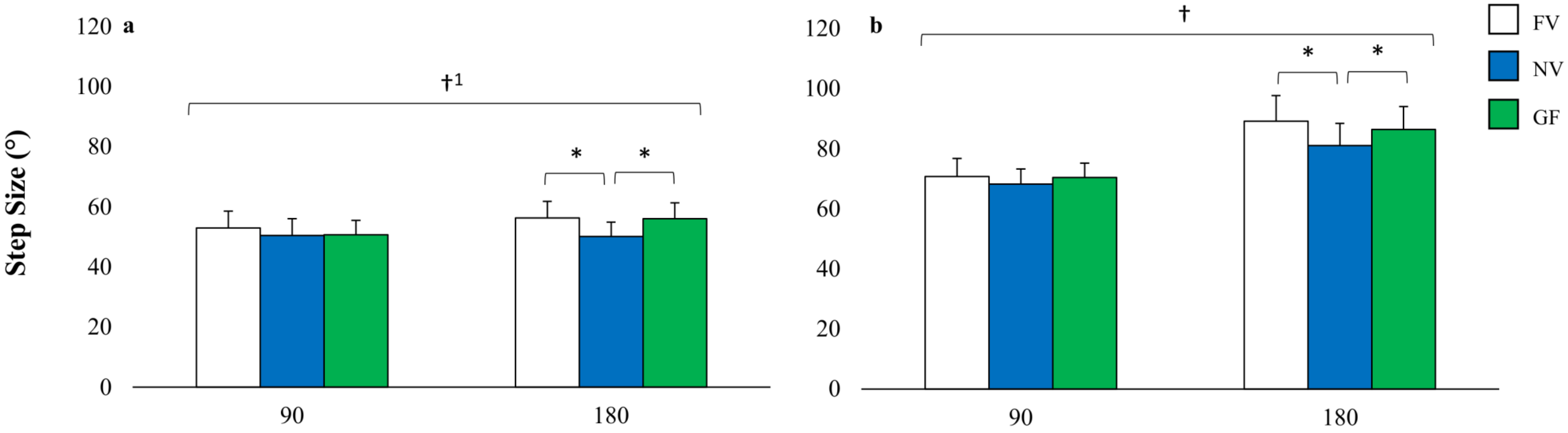

Figure 4-8: Mean step sizes for all experimental conditions. a) Mean lead step size was significantly smaller during turns to 90° during FV and GF, but there were no significant differences in step size between 90° and 180° turns during the NV trials. b) Mean trailing step size was statistically significant between 90° and 180° for all visual conditions, showing an increase in step size with increased amplitude. [1]Trailing steps during FV and GF were significantly larger than those made during NV, but only during 180° turns. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between visual conditions and brackets with daggers represent statistically significant differences between amplitude conditions.

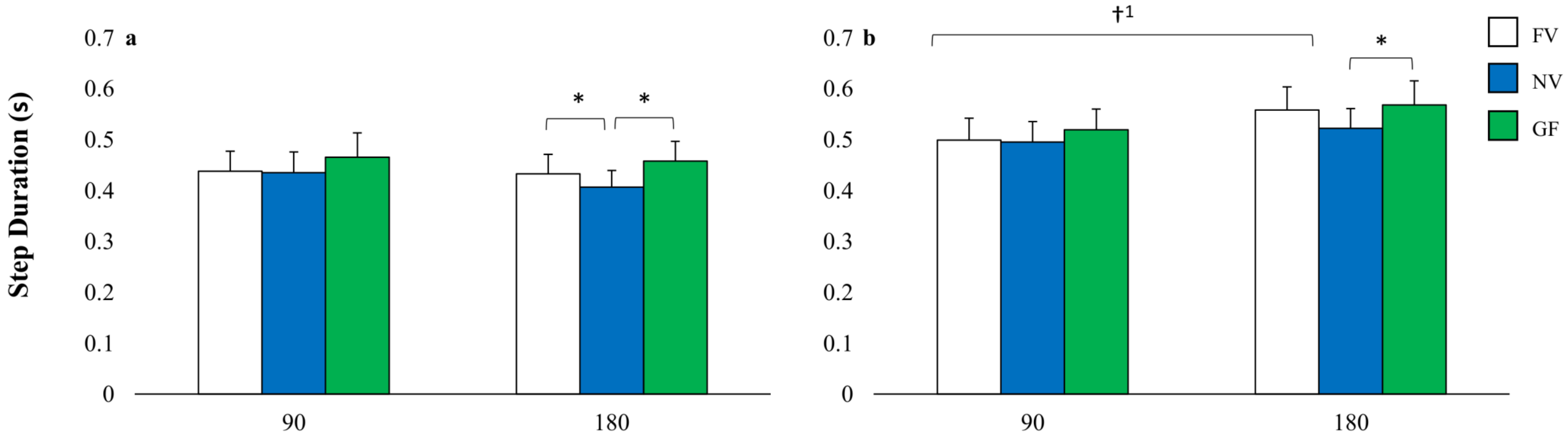

Figure 4-9: Mean durations for all experimental conditions. c) Mean lead step duration was significantly longer during FV and GF during 180° turns, but did not differ between the visual conditions during 90° turns. There were no differences in lead step duration due to turn amplitude. b) [1]Mean trailing step duration was significantly shorter during FV turns to 90° than to 180°, but there were no significantly differences due to turn amplitude in the other visual conditions. Trailing steps during 180° turns were significantly larger during GF than during NV. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between visual conditions and brackets with daggers represent statistically significant differences between amplitude conditions.

RM ANOVA was performed on the stepping frequency and found a main effect of turn amplitude ($F_{(1, 16)} = 43.79$, $P<.001$) and a main effect of visual condition ($F_{(2, 32)} = 7.39$, $P=.002$); the increase in turn amplitude from 90° to 180° caused a decrease in stepping frequency and the increased constraints on vision (i.e. first vision removal, then fixation) also caused a reduction in stepping frequency. A significant interaction between turn amplitude and visual condition was found on stepping frequency ($F_{(2, 32)} = 5.27$, $P=.01$). Pairwise comparisons showed that there were no significant differences in stepping frequency between the FV and NV conditions in either the 90° or 180° trials. However, the FV and NV stepping frequencies were significantly higher than the stepping frequency during GF for both turn amplitudes (Figure 4-10). Pearson correlation analysis between peak head velocity and stepping frequency found significant but weak relationships in the FV ($R^2 = .02$, $P=.26$), NV ($R^2 = .04$, $P<.001$) and GF ($R^2 = .08$, $P<.001$) conditions.

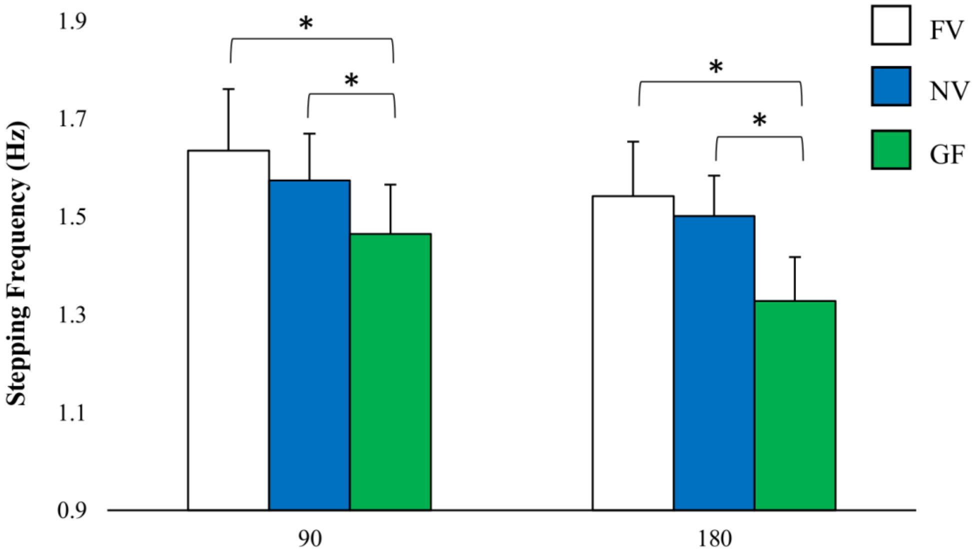

Figure 4-10: An interaction between turn amplitude and visual condition showed differences in stepping frequency between FV and NV were non-significant in both turn amplitudes, but GF caused a significant reduction in stepping frequency. There were no significant difference in stepping frequency between turn amplitudes. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between visual conditions.

4.3.5 Relative segment positions

To determine if there were effects due to visual condition on the orientation of gaze and the axial segments relative to the foot, RM ANOVA was performed on the instantaneous gaze, head, thorax and pelvis positions relative to the step foot at step initiation and step termination. Inspection of the data found observable differences between relative positions during the leading and trailing, therefore separate analyses were performed each step and a Bonferroni's correction was applied which set the new alpha at $P<.008$.

There were no effects of visual condition on any segment position at lead step initiation (Figure 4-11a) or lead step termination (Figure 4-12a). There was a main effect of visual condition at trail step initiation on gaze position ($F_{(2, 32)} = 9.35$, $P=.001$), thorax position ($F_{(2, 32)} = 5.68$, $P=.008$) and pelvis position ($F_{(2, 32)} = 6.61$, $P=.004$). There was a main effect of visual condition at trail step termination on gaze position ($F_{(2, 32)} = 18.52$, $P<.001$) and head position ($F_{(2, 32)} = 6.23$, $P=.005$).

To determine if there were differences in relative segmental positions, RM ANOVA was performed on the instantaneous gaze, head, thorax and pelvis positions at step initiation and step termination separately for each visual condition. A Bonferroni's correction was applied which set the new alpha at $P<.004$.

There were significant differences in segmental position during NV at leading step initiation ($F_{(1.126, 18.010)} = 10.34$, $P=.004$) and leading step termination ($F_{(1.109, 17.737)} =$

13.25, P=.001). Post hoc showed that gaze position was significantly ahead of the other segments during NV at leading step initiation (Figure 4-11a) and leading step termination (Figure 4-12a). There were significant differences between segment positions at trailing step initiation in FV ($F_{(1.132, 18.119)} = 15.15$, P=.001) and NV ($F_{(1.147, 18.358)} = 17.21$, P<.001) and at trailing step termination in FV ($F_{(1.340, 21.436)} = 22.95$, P<.001) and NV ($F_{(1.256, 20.094)} = 16.26$, P<.001) Post hoc found that gaze was significantly ahead of all other segments during FV at trailing step initiation and during NV, all segmental positions were significantly different from each other, except head position (Figure 4-11b). At trailing step termination, gaze was significantly ahead of all other segments during both FV and NV conditions, but there were no differences between the other segments and there were no differences between any segmental positions during GF (Figure 4-12b).

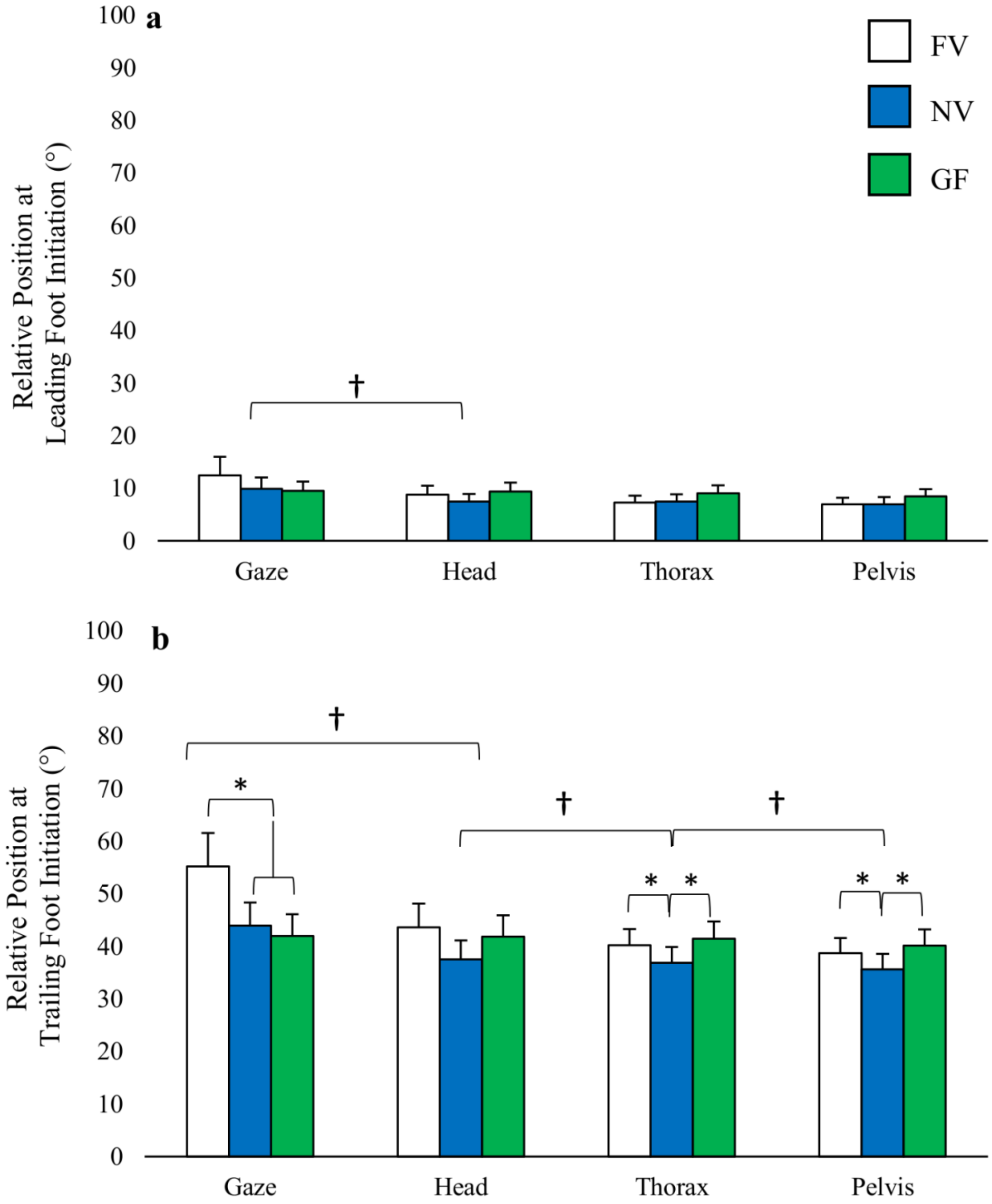

Figure 4-11: Relative segments positions (amplitude collapsed) at step initiation. a) There were no significant differences in any relative position segment due to visual condition at step initiation b) Gaze was significantly more eccentric during FV than NV or GF at trailing step initiation. Segments during GF appear *en bloc* at all step initiations. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between visual conditions and brackets with daggers represent statistically significant differences between segments.

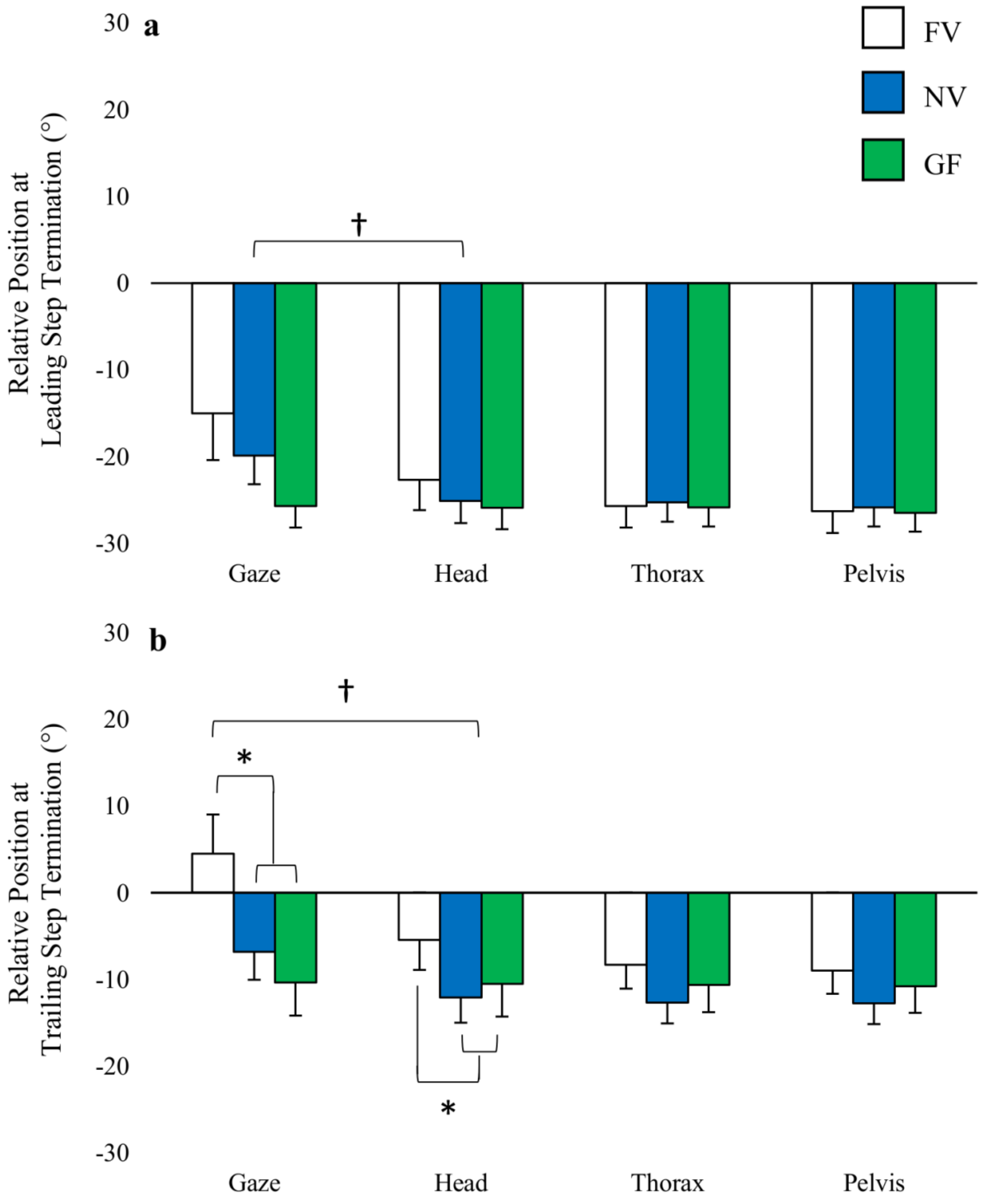

Figure 4-12: Relative segments positions (amplitude collapsed) at step termination. a) Gaze was significantly more eccentric during FV than NV or GF at leading step termination b) Gaze was significantly more eccentric during FV than NV or GF at leading step termination; gaze was significantly ahead of all other segments in both FV and NV. Segments during GF appear *en bloc* at all step terminations. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between visual conditions and brackets with daggers represent statistically significant differences between segments.

4.4 Discussion

The aim of the current study was to compare both the visual control and the oculomotor control aspects of turning by separately removing visual input and preventing eye movements. While removing visual input does slow turning and decrease fast phase characteristics i.e. fast phases are generally smaller and slower, there was no change in the overall coordination when compared with full vision turns. Conversely, preventing eye movements disrupted timing and spatial characteristics of the axial segments and the feet. When gaze was fixated, gait initiation, but not axial segment rotation, was delayed compared to both full vision and no vision turns. Throughout the turn, the relationship between head anticipation and turn speed, completely disappeared. Additionally, stepping frequency was significantly reduced during gaze fixation, but not during the no vision condition, suggesting that the ability to move one’s eyes is important in controlling stepping behaviour.

4.4.1 Gaze fixation delays step initiation and decreases stepping frequency

At the onset of reorientation our participants consistently began reorientation with the axial segments in an *en bloc* manner, which was then followed by the reorientation of the eyes (in both the FV and NV conditions) and then by the initiation of stepping. As predicted, we found remarkably similar segmental onset latencies between the full vision and no vision conditions, however, there was a significant delay in the onset of stepping in both the leading and trailing feet in the gaze fixation condition, which suggests that eye reorientation, but not visual input, has a direct influence on the initiation of gait during on-the-spot turns. Additionally, stepping frequency was reduced in the gaze fixation condition but not during the no vision condition. While it is possible that fixating gaze may have been uncomfortable for the participants as it is clearly a non-physiological approach to turning, the delays in the initial segment rotations (axial segments) were only slightly, not significantly, delayed in comparison with the full vision and no vision turns (see brackets on Table 4-1a-c). These findings support the hypothesis that oculomotor control and stepping behaviour are intrinsically linked which has been well demonstrated in precision stepping (Hollands *et al.*, 1995; Hollands and Marple-Horvat, 2001). If eye and stepping movements are part of a synergy, the results of the gaze fixation condition suggest that normal gait initiation is dependent upon the initial eye reorientation and by suppressing eye movements, gait initiation must be achieved through another pathway thus delaying onset. We have shown strong temporal relationships exist between the onset of eye and foot rotation (Table 4-1) during turning and our results are consistent with our previous study (Table 3-1) and with previous research (Hollands, Ziavra, and Bronstein, 2004). While we did find stronger temporal relationships between the axial segment onsets and the onset latency of the leading foot than between the eye and latency it is clear that inhibition of eye movement, specifically, affects stepping behaviour as preventing head-on-trunk movement during steering has been shown to disrupt segmental coordination but it does not appear to alter the timing of step initiation (Hollands, Sorensen and Patla, 2001).

A study by Reed-Jones *et al.* (2009b), investigated steering responses (i.e. axial rotation with similar temporal and spatial characteristics to actual steering) which can be induced visually by viewing (virtual) movement around a corner during stepping-in-place. The group found significant delays in the steering response, which during the free gaze condition had anticipated the movement around the corner; additionally, the top-down sequence was abolished and steering occurred *en bloc* during the fixed gaze condition. During real-world steering, the same delays in reorientation and *en bloc* coordination occur when gaze is fixed (Ambati *et al.*, 2013). While the Reed-Jones and Ambati studies found disruptions in axial coordination, it is possible that this was because steering was elicited during the course of ongoing stepping movements while our turns began from quiet stance. Due to the strong and consistent temporal relationships between the initiation of segment reorientation and stepping movements during steering which is found throughout the literature, it is unlikely that there are two separate motor commands sent for reorientation and gait initiation during steering. However, it is possible that steering during ongoing movement uses a simplified steering command to reorient the upper body which is released in coordination with ongoing stepping commands sent via the central pattern generators (Courtine and Schieppati, 2003b). When the steering synergy is released during quiet stance, it is likely that the same central pattern generators are signalled to initiate gait, which is likely why the same timing relationships between the segments and the feet are seen during both locomotor and standing turns.

Stepping behaviour similar to our results has been found in patient populations who experience oculomotor deficits. A study on spasmodic torticollis patients using LED targeted standing turns, found that patients had significantly different oculomotor performance compared to controls i.e. patients were largely unable to make single gaze shifts, even to predictable locations and foveation to the target occurred via hypometric saccades with significant temporal delays compared to controls (Anastasopoulos *et al.*, 2013). Torticollis patients also experienced significant delays in the initiation of stepping compared to not only the healthy control group, but also to Parkinson’s patients, who have well documented difficulties with turning. Both torticollis and PD patients have a reduced ability to make head-on-trunk movement despite different pathologies and both groups appear to rely more on eye movements during gaze shifts as the relative eye contribution to combined eye-head gaze shifts is larger in both torticollis and PD patients than controls (Anastasopoulos *et al.*, 2011, 2013). However, increased reliance on eye movements during whole-body gaze shifts may be a problematic strategy as oculomotor deficits in Parkinson’s patients have been hypothesized to be related to poor turn performance. Lohnes and Earhart (2011) found differences in both fast phase characteristics and turn performance between PD patients and age- and gender-matched controls while performing 180° standing turns. They showed that PD patients had a higher number of total fast phases, the amplitude and velocity of the initial fast phase were smaller and slower and their turns took longer and used more steps than the controls. A follow-up study showed that DBS was associated with a reduction in the number of fast phases, initial fast phase amplitudes and velocities were larger and faster and turn duration decreased (Lohnes and Earhart, 2012). Additionally, they found that the eye-to-head and eye-to-foot latencies decreased significantly. However, when the same cohort performed a head-restrained saccade task (i.e. saccades to fixed targets in response to an auditory cue), there were no differences in saccade latency or amplitude between the DBS on and DBS off stages, suggesting there was no improvement in oculomotor behaviour with DBS. Another group compared saccade performance in both head-restrained and head-free conditions in PD patients in DBS on and off stages and found DBS to significantly shorten saccade latency in both head conditions (Saleau *et al.*, 2008). However, the Salaeu group used a reflexive saccade paradigm rather than the volitional saccades used by Lohnes and Earhart (2012), which suggest that attentional processes may hinder DBS improvement in oculomotor control. Divided attention via dual-tasking has been shown to cause significant impairments to turn performance in PD patients, including slower velocities, increased stepping and increased frequency of FOG episodes (Spildooren *et al.*, 2010).

It is unknown, however, whether changes in oculomotor control when attention is divided due to dual tasking contributes to poor turning performance in PD.

Lastly, we found that the delay in the onset of the leading step was constant between turns to each amplitude, while the delay in the onset of the trailing step increased with increasing amplitude, which is consistent with the findings of our previous study (Chapter 3) as well as gait initiation literature which suggests that gait initiation may be controlled by two highly coordinated, but separate motor programmes for each foot (Brunt *et al*., 1999). Overall, the observed changes in stepping initiation provides strong evidence that oculomotor control is fundamentally related to stepping control and that visual input has little effect on eye-foot coordination.

4.4.2 Visual influence on intersegmental coordination

For the current study, we implemented a turn speed control measure to eliminate the behavioural changes due to turn context we found in our previous study (Chapter 3). We chose a slow turn speed because a) inter-subject variations in turn speed were smaller in the moderate condition than the fast condition in our previous study and b) a slower speed ensured stability of the head-mounted device. In our previous study, we suggested that *en bloc* turns were largely due to turn speed, whereby slower turns were performed more *en bloc* than faster turns as a direct consequence of turn speed. In the current study, we found the same association between peak segmental separations and turn speed, however, we also found that the visual condition influenced this relationship. During full vision peak head velocity accounted for approximately 34% of the variability of peak head-peak separation and when vision was removed, peak head velocity could still account for approximately a fifth of the variability in peak head-pelvis separation (Figure 4-4). However, when eye movements are restricted, the relationship between turn speed (measured using peak head velocity) is abolished and the variability in peak head-pelvis separation due to peak head velocity is only 1%. Additionally, results of the RM ANCOVA did not reach significance, demonstrating that the differences in peak head-pelvis separation between the conditions could not be due to differences in turn speed. It is clear from our results as well as many previous studies (Grasso *et al.*, 1998; Bernardin *et al.*, 2011; Authié *et al.*, 2015) that gaze anticipates the other body segments during the majority of rotation and that these anticipations occur whether or not visual information is available. Our results demonstrate that by preventing anticipatory eye movements, intersegmental coordination is disrupted, suggesting that eye movements are intrinsic to the control of this coordination.

4.4.3 Visual influence on fast phases

Comparisons of fast phase spatial characteristics between the FV and NV condition found that fast phases elicited in full vision were larger, faster and more likely to begin and end at eccentric positions within the orbit in comparison to no vision. These results differ to those of Authié (2015), who found relatively similar fast phase characteristics in full vision and no vision during complex curvature walking. The discrepancy between results are likely due to the differences in protocols, which have significantly different radii of rotations; it has been shown that during curved walking, people predictably alter their velocity according to the radius of the curvature i.e. the greater the curvature, the slower the movement velocity (Vieilledent *et al.*, 2001). While standing turns have a relatively constant radius, our previous study demonstrated that turn velocity increases with increasing turn amplitude (Chapter 3). Therefore, the relative contributions of the semi-circular and otolith organs to vestibular mediated nystagmus are likely to be significantly different between curved walking and standing turns. However, visual background characteristics have been shown to influence spatiotemporal characteristics of fast phases during passive rotation. Peak velocity of fast phases were found to be slower in the dark in alert monkeys than those elicited in a structured visual field (Ron, Robinson and Skavenski, 1972). This appeared to influence the main sequence relationship as they found that fast phases elicited in darkness had longer durations than similar amplitude fast phases elicited in the structured field. Our dataset shows a similar attenuation of the main sequence, which is that fast phases were slower during NV than FV for similar amplitude fast phases. Kaminiarz *et al*. (2009) compared the main sequence relationships of fast phases elicited during optokinetic nystagmus (OKN) versus optokinetic afternystagmus (OKAN) which is a form of nystagmus which continues after optokinetic input is removed and in the absence of head rotation. They found that the strength of the relationship between fast phase amplitude and fast phase velocity reduced from $R^2 = 0.93$ during OKN to $R^2 = 0.75$ during OKAN. This reduction in strength is similar to that of the current study where the variability in peak fast phase velocity could be attributed to fast phase amplitude approximately 54% of the time during FV and which reduced to 34% during the NV condition. Kaminiarz et al. (2009) suggested that the differences found between OKN and OKAN fast phases in their study was likely attributable to the activation of the frontal eye fields (FEF). This conclusion was made as there are differences found between in both FEF activity and main sequence relationships during voluntary saccades versus visually guided saccades and while fRMI was not performed in the Kaminiarz study, the FEF has also been shown to be active during OKN (Konen et al. 2005). Collectively, these studies show that background characteristics, specifically optokinetic input in these instances, makes a large contribution to the determination of fast phase characteristics.

The differences we found between the vision and no vision fast phase characteristics are likely due to a) the relative contribution of the optokinetic reflex, b) a gaze-anchoring mechanism or c) a combination of the two. Eye movements due to optokinetic input only are generally small in amplitude (3-4°) and have a similar frequency (2-3Hz) to that observed in this experiment (Abadi, 2002). However, if optokinetic input shows an additive effect on vestibular nystagmus, we would expect that fast phases during vision would only be around 3-4° higher than during the no vision trials. However it is clear from our amplitude distribution (Figure 4-7c) that fast phase amplitudes do not simply increase when vision is available but during vision there is a greater range of amplitudes than those elicited without visual input. A gaze anchoring mechanism is a more likely explanation for the differences between spatial characteristics in vision and no vision. Gaze anchoring may be implementing by using fast phases to identify important environmental features, which are then fixated on or 'anchored' during the slow phase portion of nystagmus, a strategy which is employed during precision stepping and obstacle crossing (Hollands *et al.*, 1995; Patla, 1997; Hollands and Marple-Horvat, 2001). However, analysis of the visual scene during turning would be necessary to confirm this hypothesis which is not possible using electro-oculography. Additionally, while gaze anchoring may serve as an additional mechanism to update the visual reference frame, it is clearly not the cause of fast phase eye movements since there are substantial similarities between gaze during vision and no vision. The consistent finding that gaze precedes head rotation during the majority of the turn, this suggests that top-down reorientation is necessary for successful motor coordination, that this is implemented via anticipatory eye movements which are an inherently stable part of the turning synergy, and that this mechanism is largely independent of vision. Furthermore, the frequency of nystagmus did not differ significantly between full vision and no vision turns. Donaghy (1980) examined the nystagmus fast phase frequency in cats and found that it did not ever exceed more than four fast phases per second. He reasoned that more frequent fast phases would be detrimental and that the stabilization of the retinal image provided by the vestibular system during the slow phase would be in vain. However, it is clearly that the frequency of fast phases is consistent both with and without visual input, therefore stabilization of the retinal image does not appear to drive or limit the elicitation of fast phases. The conclusion about the apparent NFPF threshold may still hold true though. Gaze stabilization is certainly important, both with and without vision, otherwise nystagmus would not occur. However, intermittent gaze stabilisation may serve as a calibration for subsequent body rotation and stabilisation during turning.

4.4.4 Gaze fixation disrupts intersegmental coordination and stepping behaviour

While all turns began in an *en bloc* manner, the course of the turns during full vision and no vision are clearly organised in a top-down manner, whereby the eyes anticipate the head and the head anticipates the other axial segments (Bernardin *et al.*, 2011) as is demonstrated in Figure 4-11 and Figure 4-12. However, visual inspection of the gaze fixation condition in these figures suggest that the entire turn is performed *en bloc*, which was also supported by the RM ANOVA results of segmental positions at step initiation and termination (4.3.6) as well as the regression analysis between peak head velocity and peak head-pelvis separation (Figure 4-4). These results demonstrate that eye movements influence intersegmental coordination, specifically during turning as has been previously demonstrated during visually elicited turns (Reed-Jones *et al.*, 2009b) and turns which occur during ongoing locomotion (Ambati *et al.*, 2013).

Constraining visual information had significant effects on stepping frequency. While the decrease in stepping frequency was slight and non-significant between the FV and NV conditions, the decrease in stepping frequency was significant in the GF condition. Inhibiting eye movements may have the same detrimental effect on step behaviour during gait as it does during gait initiation. Central pattern generators (CPG) are thought to control the rhythmic pattern of stepping which occurs during locomotion (Duysens and Van de Crommert, 1998). It is believed the commands which initiate and terminate activity of the CPGs come from supraspinal levels. If the turning synergy is a sequenced motor programme which elicits reorientation in a cephalo-caudal manner, then the signal from the initial head or eye rotation should be sent to the spinal cord to initiate gait. If the order of segment reorientation demonstrated by our participants represents the ‘true’ sequence of the turning synergy, as was hypothesized by Cinelli and Warren (2012), then the signal sent from the eye should be the signal which elicits CPG activation. If such is the case, then gaze fixation would eliminate the signal from the eye to the CPG and stepping would not occur. However, it is evident that stepping does occur during gaze fixation but that it is delayed. So the question remains, where does the signal to initiate gait come from during gaze fixation? It is potentially through afferent activity from the vestibular system or perhaps via efference copy of the original turning synergy. Efference copy is an internal copy of the intended motor signal that is used to compare actual movement with intended movement (Bruneo, 2010). The absence of the original signal from the turning synergy would require either integration of afferent vestibular information or the transformation of the efference copy of the turning synergy; both integration and transformation processes would likely take time and result in a significant delay in activation of the CPG.

4.5. Does voluntarily fixating gaze require attention?

As stated in section 4.4.1 (see page 109-110), dual-tasking during turning has been shown to cause significant alterations in turning behaviour, specifically in PD and stroke patients. It could be argued that the gaze fixation condition in the current study is cognitively demanding and requires a level of attention beyond that which is required during normal free gaze turns. A study by Yardley *et al*. (1999) suggests that VOR suppression via gaze fixation does in fact require cognitive effort. In the study, participants were passively rotated in a motorised chair in darkness and were subsequently asked to estimate the magnitude of their rotation by using a joystick to return to their starting position. During the return rotation, reaction times, measured by push buttons near the participants' thumbs, in response to auditory stimuli were measured. Participants performed the reaction task during both a free gaze and fixed gaze condition. Results indicated that reaction times during fixation were slower than those during free gaze. While it is clear that there is an effect of fixating gaze on the reaction time, it does not necessarily indicate that this is directly due to the involvement of cognitive processes. It is well established that eye movements often precede movements of the hand (Johansson *et al*., 2001) and it is possible that even simple movements of the thumb, especially when vision is unavailable, may rely on eye proprioceptive signals enabled by eye movements towards the target or goal location. The task used by Yardley, set out to determine whether attentional resources are required when determining orientation using *only* vestibular information, which may itself enhance cognitive effort. Our gaze fixation task did not require this level of attention to complete the task as vestibular, proprioceptive and peripheral visual inputs were freely available. Additionally, they rotated participants to six different magnitudes while our protocol only had two, further limiting the amount of attention required to accurately perform a turn. The group also performed the orientation task, i.e. returning the chair to the starting position, during serial subtraction, and found the addition of this cognitive task decreased the ability of the participants to accurately estimate the magnitude of their rotation. Unfortunately the group did not have participants perform the auditory task during serial subtraction, nor were they made to perform the reorienting task during gaze fixation. Comparisons between the gaze fixation condition of the current study and the serial subtraction study described in Chapter 6, suggest that gaze fixation does not work through the same mechanisms as serial subtraction. If gaze fixation did require a level of attention, it is likely that the changes in behaviour due to both gaze fixation and serial subtraction, which is known to require attention, would be the same. However, while we found delays at turn initiation in both studies, we only found significant delays during gait initiation when gaze was fixed, while serial subtraction delayed the entire turn. Additionally, the neural substrates for serial subtraction and gaze fixation do not appear to overlap. Functional magnetic resonance imaging (fMRI) studies have shown that serial subtraction causes activation in both the prefrontal cortex and in the putamen (Wang *et al*., 2005), an area of the basal ganglia (BG), which is known to be involved in movement initiation (Denny-Brown, and Yanagisawa, 1976; Hauber, 1998). Additionally, the neural substrate of VOR suppression, which is enabled via gaze fixation, is located subcortically in the flocculus region of the cerebellum (Schmid, Zambarbieri and Magenes, 1981).

4.6 Conclusion

Eye and body coordination during large whole-body turns is preserved in the absence of visual input, however, inhibiting eye movement during turning causes significant disruptions to stepping characteristics including the initial onset of gait as well as frequency at which stepping occurs throughout the turn. Preventing eye movements also disrupts the intersegmental coordination of the axial segments by effectively removing the relationship between turn speed and the positional relationships between the head and pelvis. These findings support previous suggestions that eye movement control is intrinsic to the turning synergy and that turning behaviour is controlled by a phylogenetically old mechanism that serves to realign gaze, i.e. turns are controlled via whole-body gaze shifts.

Chapter 5

The effects of unilateral neck vibration on eye and whole-body coordination during standing turns

5.1 Introduction

Postural stability relies on input from visual, vestibular and proprioceptive signals, however, the relative contributions of each system to controlling behaviour is largely context-based i.e. dependent on the motor activity, the goal of the task and ultimately, the available sensory input. This phenomenon is well demonstrated by Ivanenko *et al.* (1999), who investigated how gaze position affects postural sway during manipulations of either the vestibular or proprioceptive system. Participants stood on a force platform in darkness while fixating a red light presented within a pair of goggles. Gaze was manipulated via either head-on-trunk rotations to 0°, ±45° or ±90° or eye-in-orbit rotations to 0° or ±30°. During one half of the experiment, the vestibular system was perturbed using galvanic vestibular stimulation (GVS), which uses electrical current to directly stimulate the vestibular nerve (Fitzpatrick and Day, 2004). The cathode, which increases vestibular afferent activity, was placed on the right mastoid. The other half of the experiment used dorsal neck muscle vibration to perturb proprioception. During GVS trials, sway aligned orthogonally to the naso-occipito axis (i.e. in line with the axis that runs between the two ears) and was directed towards the anode. During neck vibration, the direction of sway typically aligned with the direction of gaze. The prominent effect of gaze position on sway during the stimulation of neck proprioception led the authors to conclude that proprioceptive signals are processed within the context of visual control. Accurate signals from neck proprioceptors is undoubtedly important for oculomotor control, as patients with compromised vestibular systems have been shown to upregulate neck muscle proprioceptive information, evident by the enhanced gain of the COR in comparison to healthy controls (Bronstein and Hood, 1986). These clear interactions between gaze and neck proprioception might indicate that the enhanced VOR gain seen during active head rotations (Barnes, 1979) may be due to the integration of proprioceptive signals with the vestibular signals generated during rotation. Additionally, neck muscle vibration can elicit nystagmus-like eye movements (Lennerstrand, Han and Velay, 1996; Popov *et al.*, 1999). This leads to the question, do the eye movements induced through vibration work through the same mechanism as those during active head rotation and if so, can vibration be used to modulate eye movement behaviour during turning?

In addition to its effects on oculomotor behaviour, neck muscle vibration influences stepping behaviour. Dorsal neck muscle vibration causes slow forward motion while stepping-in-place in darkness; however, stepping frequency does not appear to be affected (Ivanenko, Grasso and Lacquaniti, 2000). When vibration is switched to the lateral neck muscles and applied asymmetrically during stepping-in-place, the body rotates away from the side of vibration (Bove, Courtine and Schieppati, 2002). Interestingly, lateral neck muscle vibration did not induce head rotation, which the authors used to conclude that active head rotation is not required to activate the neural circuits responsible for eliciting turns. Lateral neck muscle vibration causes deviations in trajectory towards the side of stimulation during forward locomotion in darkness (Bove *et al.*, 2001) and dorsal neck vibration causes acceleration in the direction of gaze during treadmill locomotion (Ivanenko, Grasso and Lacquaniti, 2000). It is possible that the CNS interprets neck muscle vibration as actual head rotation and that this is sufficient to elicit steering behaviour. Unfortunately, the sequence of segmental latencies were not measured in the vibration during stepping studies, which makes comparisons with actual turning difficult. Therefore it remains unknown whether the rotation observed during neck muscle vibration may be a proprioception-elicited steering synergy. Additionally, the only information available about the effects of directly manipulating neck proprioception on steering is from studies which have shown unintended deviations due to neck vibration. To date there have been no studies using neck muscle vibration during active whole-body rotations.

The aim of the current study is to determine the extent of the influence of neck proprioception on motor coordination and stability during large amplitude whole-body rotations (180°). Objectives were to: a) determine whether manipulating neck proprioception causes disruptions in intersegmental coordination b) to determine if neck muscle proprioceptors influence oculomotor characteristics and c) determine if neck vibration alters stepping behaviour. We predicted that i) perceived head-on-trunk rotation would alter intersegmental coordination, ii) vibration would alter fast phase characteristics in a directional manner (i.e. ipsilateral and contralateral neck muscle vibration will have different effects) and iii) stepping characteristics would show systematic changes due to vibration.

5.2 Methods

5.2.1 Participants

Twelve healthy young adults, mean age 20.59 years (± 1.04 *SD*) volunteered for the study. The experimental protocol was approved by the Liverpool John Moores Research Ethics Committee (REC) and all participants gave written and informed consent. Participants were excluded if neurological, musculoskeletal, or cognitive impairments were reported, or if taking medication for anxiety and/or dizziness or used an assistive walking device. Visual testing was performed using the Freiburg Vision Test (FrACT) and included an examination for monocular and binocular visual acuity using the Landolt C test (Bach, 1996). All participants had normal or corrected to normal visual acuity (20/20 or better).

5.2.2 Protocol

Neck proprioception was manipulated via vibration using a Pico Vibe (9 millimetre diameter, 25 millimetre length; Precision Microdrives Limited, London) which was placed along the belly of the sternocleidomastoid on both sides of the neck and taped in place to ensure a maintained position throughout the experiment. The vibrators remained taped in place, but turned off, during control conditions. To confirm that vibration was indeed eliciting a response in the muscle spindle, quiet stance and stepping-in-place were measured during a no vibration control condition and with unilateral vibration on either the right or left side of the neck. The quiet stance and stepping trials were performed blindfolded for 30 seconds each. During right and left side vibration, stimulation began simultaneously with the beginning of the trial. Five trials were performed in each condition for a total of 30 trials. During stepping-in-place trials, path of progression and direction of progression were calculated using the X and

Y displacement of the participant. Path of progression was determined using the Pythagorean Theorem, where the hypotenuse represents the path of progression. Direction of progression was calculate by determining the angle between the Y displacement and the progression (Figure 5-1).

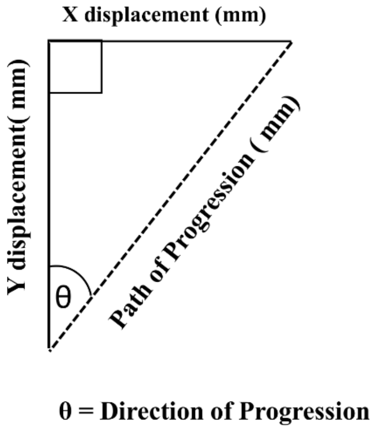

Figure 5-1: Calculation of path of progression using the Pythagorean Theorem and direction of progression by determining theta (θ).

During turning trials, neck vibration began at the same time as presentation of the turn demonstration videos, as previous studies have shown that the effects of vibration are not instantaneous and can have a delay of up to 10 seconds (Bove, Courtine and Schieppati, 2002). The delay between the presentation of the video and the auditory cue to turn was variable, between 8-10 seconds for every trial. The vibrators remained on throughout the trial, which lasted for 8 seconds. In addition to proprioceptive manipulation, vision was removed for half the trials according to the no vision protocol described in Chapter 4. Turns were performed to either the left or right to 180° under one of the following six conditions: full vision without vibration (FV), full vision with ipsilateral vibration (FVIV), full vision with contralateral vibration (FVCV), no vision without vibration (NV), no vision with ipsilateral vibration (NVIV) and no vision contralateral vibration (NVCV). Trial order was fully randomised for each participant. A total of 5 trials were recorded for each condition for a total of 60 trials.

5.2.3 Statistical analysis

The statistical package SPSS (22.0) was used for all statistical procedures. A one-way RM ANOVA was performed on the quiet stance and stepping variables. During turning, a 2 x 2 x 3 RM ANOVA was performed on all dependent variables with direction (left or right), visual condition (full vision or no vision) and vibration condition (no vibration, ipsilateral or contralateral) as repeated measure factors. No effects of turn direction (left versus right) were found; therefore the presented results are from a 2 x 3 RM ANOVA design. RM ANCOVA was subsequently performed on significant results to control for turn speed using peak head velocity as a time-varying covariate. Pearson's Product moment correlation was used to determine the strength of relationships between the dependent variables. Main sequence analysis was performed on fast phase data for all experimental conditions; correlation coefficients were then compared using a Fisher transformation. Frequency distribution analysis was performed on fast phase characteristics and Kolmogorov-Smirnov Z was run to determine differences between the distributions from each experimental condition. All mean values are presented with standard deviations unless otherwise stated. Statistical significance was set at $P<.05$. A Bonferroni's correction was used for multiple comparisons.

5.3 Results

5.3.1 Quiet stance

RM ANOVA was run on medio-lateral (ML) and anterior-posterior (AP) sway amplitude, mean and SD of the sway curve using the displacement of the LASI marker. There were no significant effects of vibration in either the ML or AP direction.

5.3.2 Stepping-in-place

Peak head-thorax yaw separation, path length, path direction and stepping frequency during stepping-in-place trials were calculated. RM ANOVA was performed and found a main effect on peak head-thorax angular separation ($F_{(2, 22)} = 5.57$, $P=.011$). Pairwise comparisons found that head-thorax separation significantly decreased during vibration, but there were no differences between left and right side vibration. A main effect was found on path length ($F_{(2, 22)} = 3.64$, $P=.043$); post hoc comparisons showed that participants walked furthest during left side vibration. There were no main effects on path direction or stepping frequency.

Observation of the participants and the dataset showed large variability in behaviour between the participants and that the direction of progression was not systematic between conditions. Figure 5-2 shows progression plots from all trials for each participant.

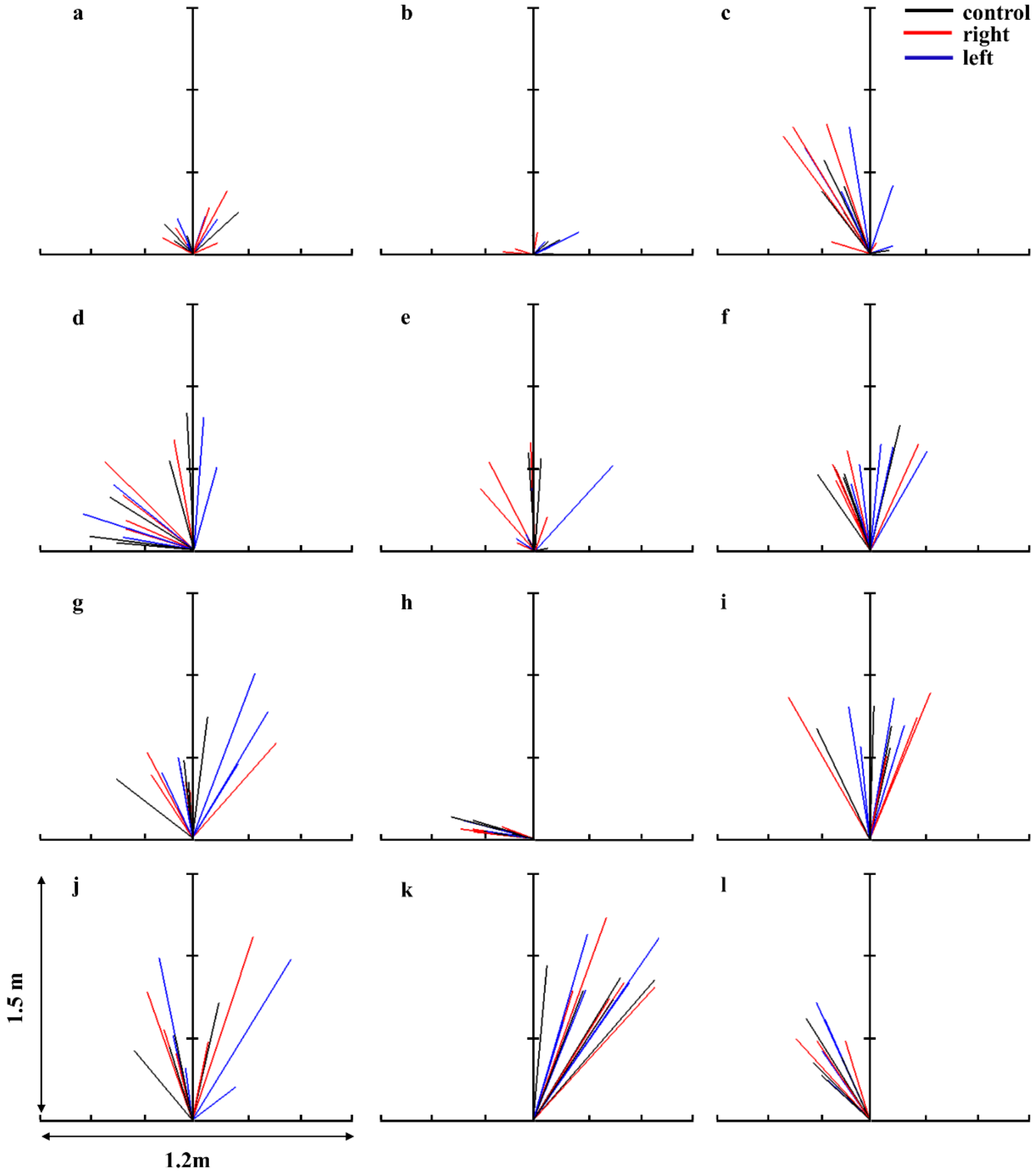

Figure 5-2: Path of progression from all stepping-in-place trials, the origin represents the initial position of the participant. There were no systematic directions of progression between the participants due to the vibration. Participant behaviour varied greatly; some participants rotated significantly more than they progressed (h), some rotated in the same direction for all trials (l). However, most participants generally rotated and progressed to some extent during all conditions.

5.3.3 Segment onset latencies

The sequence of segment reorientation onset began with the head or thorax in all conditions, followed by the pelvis, then the eye and finally the leading and trailing feet (Figure 5-3). The mean onsets were not significantly different between the head and thorax or between the eye and leading foot, but were significantly different between all other segment pairs. There were no main effects of vision or vibration on any of the segment onset latencies, however, there was an interaction between vision and vibration for all segment latencies (eye: $F_{(2, 22)} = 3.59$, P=.045; head: $F_{(2, 22)} = 3.70$, P=.041; thorax: $F_{(2, 22)} = 4.51$ P=.023; pelvis: $F_{(1.374, 15.114)} = 3.69$ P=.042; leading foot: $F_{(2, 22)} = 4.66$ P=.021; trailing foot: $F_{(2, 22)} = 5.22$, P=.014). Post hoc analysis showed the interaction between visual and vibration conditions lead to significantly later segment onset latencies in the FV condition than in any other condition (Figure 5-3). Pearson’s product moment correlation analysis revealed significant correlations (P<.001) between all segment onset latencies.

To determine if the differences in onset latencies between conditions were due to differences in turn speed between the conditions, RM ANCOVA was performed on all segment onset latencies using peak head yaw velocity as a time-varying covariate. However, there were no significant effects of turn speed on any segment onset latency. The effects of vibration and vision were preserved when peak head yaw velocity was added as a covariate demonstrating that turning speed cannot explain the effects.

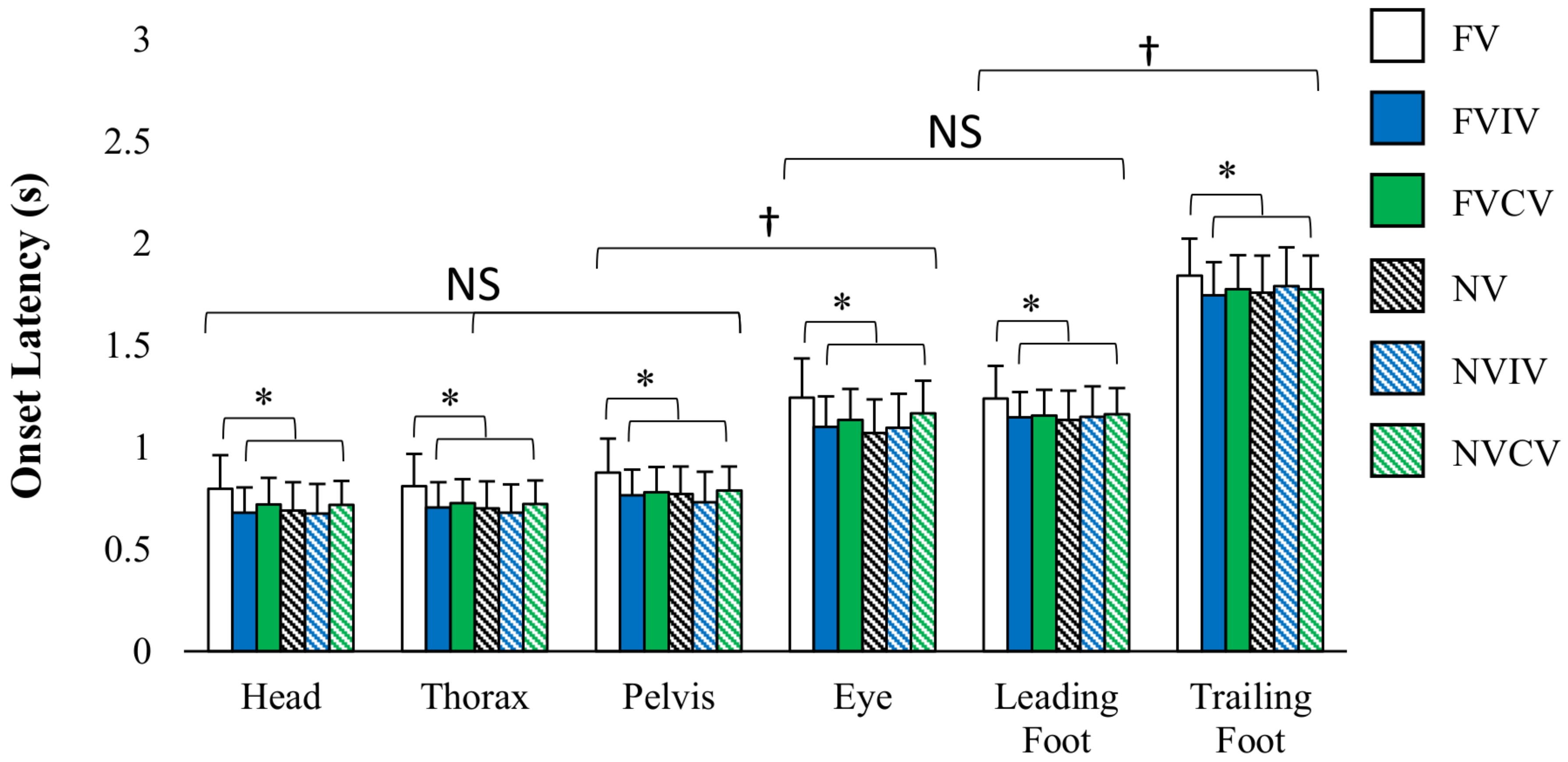

Figure 5-3: Mean onset latencies for all segments in all conditions. An interaction was found on all segment onset latencies which showed that segment onsets were significantly later during FV than all other conditions. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between experimental conditions and brackets with daggers represent statistically significant differences between segments.

Table 5-1a

Mean onset latencies (ms) for all participants during FV conditions and results of Pearson's product moment correlation (R^2) between the onset latencies of the eye, axial body segments and foot rotation from all participants during all FV trials.

			Eye	**Head**	**Thorax**	**Pelvis**	**Leading Foot**	**Trailing Foot**
Eye	1244 ± 530	Pearson correlation		0.91	0.86	0.70	0.81	0.66
		Sig. (2-tailed)		<.001	<.001	<.001	<.001	<.001
Head	798 ± 455	Pearson correlation	0.91		0.91	0.73	0.83	0.71
		Sig. (2-tailed)	<.001		<.001	<.001	<.001	<.001
Thorax	809 ± 442	Pearson correlation	0.86	0.91		0.71	0.80	0.68
		Sig. (2-tailed)	<.001	<.001		<.001	<.001	<.001
Pelvis	877 ± 461	Pearson correlation	0.70	0.73	0.71		0.74	0.70
		Sig. (2-tailed)	<.001	<.001	<.001		<.001	<.001
Leading Foot	1239 ± 446	Pearson correlation	0.81	0.83	0.80	0.74		0.89
		Sig. (2-tailed)	<.001	<.001	<.001	<.001		<.001
Trailing Foot	1841 ± 503	Pearson correlation	0.66	0.71	0.68	0.70	0.89	
		Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	

N = 117

Table 5-1b

Mean onset latencies (ms) for all participants during FVIV conditions and results of Pearson's product moment correlation (R^2) between the onset latencies of the eye, axial body segments and foot rotation from all participants during all FVIV trials.

			Eye	**Head**	**Thorax**	**Pelvis**	**Leading Foot**	**Trailing Foot**
Eye	1101 ± 417	Pearson correlation		0.89	0.78	0.56	0.63	0.71
		Sig. (2-tailed)		<.001	<.001	<.001	<.001	<.001
Head	681 ± 338	Pearson correlation	0.89		0.85	0.60	0.68	0.55
		Sig. (2-tailed)	<.001		<.001	<.001	<.001	<.001
Thorax	705 ± 343	Pearson correlation	0.78	0.85		0.59	0.66	0.56
		Sig. (2-tailed)	<.001	<.001		<.001	<.001	<.001
Pelvis	766 ± 345	Pearson correlation	0.56	0.60	0.59		0.53	0.54
		Sig. (2-tailed)	<.001	<.001	<.001		<.001	<.001
Leading Foot	1147 ± 342	Pearson correlation	0.63	0.68	0.66	0.53		0.88
		Sig. (2-tailed)	<.001	<.001	<.001	<.001		<.001
Trailing Foot	1746 ± 446	Pearson correlation	0.71	0.55	0.56	0.54	0.88	
		Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	

N = 119

Table 5-1c

Mean onset latencies (ms) for all participants during FVCV conditions and results of Pearson's product moment correlation (R^2) between the onset latencies of the eye, axial body segments and foot rotation from all participants during all FVCV trials.

			Eye	Head	Thorax	Pelvis	Leading Foot	Trailing Foot
Eye	1135 ± 422	Pearson correlation		0.91	0.86	0.70	0.81	0.66
		Sig. (2-tailed)		<.001	<.001	<.001	<.001	<.001
Head	721 ± 360	Pearson correlation	0.91		0.91	0.73	0.83	0.71
		Sig. (2-tailed)	<.001		<.001	<.001	<.001	<.001
Thorax	727 ± 325	Pearson correlation	0.86	0.91		0.71	0.80	0.68
		Sig. (2-tailed)	<.001	<.001		<.001	<.001	<.001
Pelvis	781 ± 342	Pearson correlation	0.70	0.73	0.71		0.74	0.70
		Sig. (2-tailed)	<.001	<.001	<.001		<.001	<.001
Leading Foot	1155 ± 353	Pearson correlation	0.81	0.83	0.80	0.74		0.89
		Sig. (2-tailed)	<.001	<.001	<.001	<.001		<.001
Trailing Foot	1776 ± 458	Pearson correlation	0.66	0.71	0.68	0.70	0.89	
		Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	

N = 117

Table 5-1d

Mean onset latencies (ms) for all participants during NV conditions and results of Pearson's product moment correlation (R^2) between the onset latencies of the eye, axial body segments and foot rotation from all participants during all NV trials.

			Eye	**Head**	**Thorax**	**Pelvis**	**Leading Foot**	**Trailing Foot**
Eye	1071 ± 457	Pearson correlation		0.92	0.83	0.61	0.74	0.59
		Sig. (2-tailed)		<.001	<.001	<.001	<.001	<.001
Head	681 ± 385	Pearson correlation	0.92		0.89	0.69	0.78	0.66
		Sig. (2-tailed)	<.001		<.001	<.001	<.001	<.001
Thorax	702 ± 368	Pearson correlation	0.83	0.89		0.66	0.77	0.65
		Sig. (2-tailed)	<.001	<.001		<.001	<.001	<.001
Pelvis	772 ± 372	Pearson correlation	0.61	0.69	0.66		0.59	0.54
		Sig. (2-tailed)	<.001	<.001	<.001		<.001	<.001
Leading Foot	1134 ± 396	Pearson correlation	0.74	0.78	0.77	0.59		0.85
		Sig. (2-tailed)	<.001	<.001	<.001	<.001		<.001
Trailing Foot	1759 ± 501	Pearson correlation	0.59	0.66	0.65	0.54	0.85	
		Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	

N = 115

Table 5-1e

Mean onset latencies (ms) for all participants during NVIV conditions and results of Pearson's product moment correlation (R^2) between the onset latencies of the eye, axial body segments and foot rotation from all participants during all NVIV trials.

			Eye	**Head**	**Thorax**	**Pelvis**	**Leading Foot**	**Trailing Foot**
Eye	1096 ± 458	Pearson correlation		0.89	0.87	0.67	0.75	0.64
		Sig. (2-tailed)		<.001	<.001	<.001	<.001	<.001
Head	676 ± 402	Pearson correlation	0.89		0.90	0.66	0.75	0.64
		Sig. (2-tailed)	<.001		<.001	<.001	<.001	<.001
Thorax	680 ± 382	Pearson correlation	0.87	0.90		0.66	0.74	0.62
		Sig. (2-tailed)	<.001	<.001		<.001	<.001	<.001
Pelvis	732 ± 410	Pearson correlation	0.67	0.66	0.66		0.70	0.61
		Sig. (2-tailed)	<.001	<.001	<.001		<.001	<.001
Leading Foot	1150 ± 414	Pearson correlation	0.75	0.75	0.74	0.70		0.88
		Sig. (2-tailed)	<.001	<.001	<.001	<.001		<.001
Trailing Foot	1792 ± 524	Pearson correlation	0.64	0.64	0.62	0.61	0.88	
		Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	

N = 116

Table 5-1f

Mean onset latencies (ms) for all participants during NVCV conditions and results of Pearson’s product moment correlation (R^2) between the onset latencies of the eye, axial body segments and foot rotation from all participants during all NVCV trials.

			Eye	**Head**	**Thorax**	**Pelvis**	**Leading Foot**	**Trailing Foot**
Eye	1166 ± 443	Pearson correlation		0.93	0.78	0.57	0.65	0.60
		Sig. (2-tailed)		<.001	<.001	<.001	<.001	<.001
Head	718 ± 328	Pearson correlation	0.93		0.83	0.58	0.65	0.60
		Sig. (2-tailed)	<.001		<.001	<.001	<.001	<.001
Thorax	723 ± 317	Pearson correlation	0.78	0.83		0.61	0.61	0.55
		Sig. (2-tailed)	<.001	<.001		<.001	<.001	<.001
Pelvis	789 ± 327	Pearson correlation	0.57	0.58	0.61		0.57	0.55
		Sig. (2-tailed)	<.001	<.001	<.001		<.001	<.001
Leading Foot	1162 ± 356	Pearson correlation	0.65	0.65	0.61	0.57		0.88
		Sig. (2-tailed)	<.001	<.001	<.001	<.001		<.001
Trailing Foot	1776 ± 455	Pearson correlation	0.60	0.60	0.55	0.55	0.88	
		Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	

N = 115

5.3.4 Head stabilisation

To examine the effects of the neck vibration on head stability, RM ANOVA was performed on the mean standard deviations of the head displacement, velocity and acceleration profiles in the pitch and roll planes. There were no main effects or interactions between vision and vibration on the SD in either the pitch or roll displacements. There was a main effect of vibration on the head pitch velocity SD ($F_{(2, 22)} = 11.09$, $P<.001$) which showed that the head pitch velocity was significantly less variable during both IV and CV than without vibration for both vision conditions (Table 5-1). There were main effects of both vision ($F_{(1, 11)} = 22.76$, $P=.001$) and vibration ($F_{(2, 22)} = 4.35$, $P=.026$) on head roll velocity SD whereby both removal of vision and the application of neck vibration decreased head roll velocity variability. There were main effects of both vision ($F_{(1, 11)} = 14.02$, $P=.003$) and vibration ($F_{(2, 22)} = 10.53$, $P=.001$) on head roll acceleration SD, which showed removal of vision and application of vibration both decreased the variability in head roll acceleration.

There were main effects of vision ($F_{(1, 11)} = 16.50$, $P=.002$) and vibration ($F_{(2, 22)} = 9.65$, $P=.001$) and a significant interaction between vision and vibration ($F_{(2, 22)} = 6.89$, $P=.005$) on head pitch acceleration SD. Main effects showed that both removal of vision and application of vibration decreased variability. Post hoc analysis found that the head pitch acceleration was significantly more variable in the FV condition than either FVIV ($P=.028$) or FVCV ($P=.016$), but FVIV and FVCV were not significantly different from one another. During no vision trials head pitch acceleration SD was significantly more variable during NV than NVIV ($P=.040$), but was not significantly different from NVCV. Additionally, the head pitch acceleration SD was significantly less variable during NVIV than NVCV ($P=.035$).

To determine if changes in head stability were due to changes in turn speed, RM ANCOVA was performed on the significant RM ANOVA results. Main effects due to turn speed were found on all dependent variables: head pitch velocity SD (F (1, 60.235) = 17.14, P<.001), head roll velocity (F (1, 60.608) = 7.23, P=.009), head pitch acceleration SD (F (1, 64.501) = 17.55, P<.001) and head roll acceleration SD (F (1, 64.945) = 9.21, P=.003). The effects of vibration and vision failed to reach significance when peak head yaw velocity was added as a covariate demonstrating that turning speed can explain the effects.

5.3.5 Fast phase characteristics

RM ANOVA was performed on the initial and maximum fast phase characteristics and found no main effects of vibration on any dependent variable. There was a main effect of visual condition on the initial fast phase amplitude ($F_{(1, 11)} = 10.26$, $P=.008$), the initial fast phase velocity ($F_{(1, 11)} = 16.62$, $P=.002$), the initial peak fast phase acceleration ($F_{(1, 11)} = 9.15$, $P=.012$), maximum fast phase amplitude ($F_{(1, 11)} = 44.09$, $P<.001$), peak fast phase velocity ($F_{(1, 11)} = 52.37$, $P<.001$) and the peak fast phase acceleration ($F_{(1, 11)} = 10.99$, $P=.007$) (Table 5-2). There were interactions between vision and vibration on the maximum fast phase amplitude ($F_{(2, 22)} = 4.58$, $P=.041$) and the peak fast phase velocity ($F_{(2, 22)} = 5.2$, $P=.014$). Post hoc analysis found no significant differences in maximum fast phase amplitude between the conditions, however mean data shows that max fast phases were larger in FVIV and FVCV than FV, but were smaller during than NV during NVIV and NVCV conditions. The peak fast phase velocity was significantly faster in the FVIV condition than the FV condition ($P=.022$) and was significantly slower in the NVIV condition than the NV condition ($P=.012$) trials, but there were no significant differences between the other vibration condition pairs in either vision conditions (Figure 5-4). There were no main effects of or interactions between vision and vibration on the nystagmus fast phase frequency.

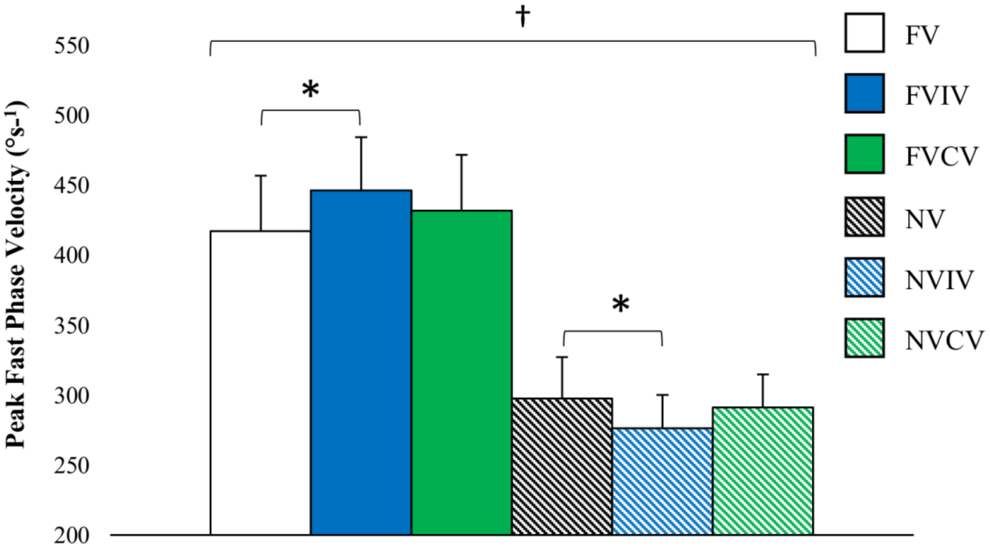

Figure 5-4: Significant interactions between vision and vibration on peak fast phase velocity. Fast phases were significantly faster in the FVIV condition than the FV condition, however, during NVIV, fast phases were significantly slower than in NV. Peak fast phase velocity was significantly higher during conditions with vision. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between vibration conditions and brackets with daggers represent statistically significant differences between visual conditions.

To determine if changes in head stability were due to changes in turn speed, RM ANCOVA was performed on the significant RM ANOVA results. The effects of vibration and vision were preserved when peak head yaw velocity was added as a covariate demonstrating that turning speed cannot explain the effects.

Main sequence analysis was performed using fast phase amplitude versus fast phase velocity for all conditions (Figure 5-5). No significant differences were found between any visual or vibration conditions.

Frequency distribution analysis was performed on eye-in-orbit position at fast phase onset and fast phase end, fast phase amplitude and fast phase velocity for all fast phases measured. A Kolmogorov-Smirnov Z test was performed between each pair of conditions in each fast phase characteristic to determine differences between the distributions. However, no significant differences were found between any of the conditions in any fast phase characteristic.

Table 5-2

Mean and standard deviations for initial and maximum/peak fast phase characteristics as well as fast phase frequency measurements.

		No Vibration	Ipsilateral Vibration	Contralateral Vibration
Initial Fast Phase Amplitude (°)	Vision	16.53 ± 13.60	15.91 ± 12.73	14.90 ± 13.89
	No Vision	10.39 ± 8.92	9.23 ± 7.01	9.41 ± 6.98
Maximum Fast Phase Amplitude (°)	Vision	27.44 ± 10.25	29.74 ± 9.86	28.28 ± 10.10
	No Vision	20.71 ± 7.48	19.32 ± 7.81	19.69 ± 6.41
Initial Fast Phase Velocity (°s^{-1})	Vision	254.27 ± 92.99	271.35 ± 109.16	248.99 ± 113.90
	No Vision	175.76 ± 66.18	167.09 ± 63.39	168.90 ± 60.85
Peak Fast Phase Velocity (°s^{-1})	Vision	417.30 ± 109.56	446.43 ± 105.32	431.98 ± 110.36
	No Vision	297.77 ± 81.39	276.29 ± 66.43	291.29 ± 65.10
Initial Fast Phase Acceleration (°s^{-2})	Vision	35896.92 ± 22293.36	39696.17 ± 25332.24	36139.64 ± 24494.71
	No Vision	20344.18 ± 11165.73	19168.58 ± 8422.27	19351.32 ± 8691.98
Peak Fast Phase Acceleration (°s^{-2})	Vision	53491.04 ± 27571.10	56370.69 ± 28992.59	55093.93 ± 30858.33
	No Vision	35374.19 ± 14899.98	31745.00 ± 11275.61	33193.16 ± 10449.03
Number of Fast Phases (N)	Vision	8.32 ± 2.48	8.12 ± 2.43	8.74 ± 2.49
	No Vision	9.06 ± 2.76	9.24 ± 2.56	8.92 ± 2.79
Nystagmus Fast Phase Frequency (Hz)	Vision	2.82 ± 0.83	2.69 ± 0.84	2.83 ± 0.77
	No Vision	2.73 ± 0.88	2.70 ± 0.85	2.71 ± 0.91

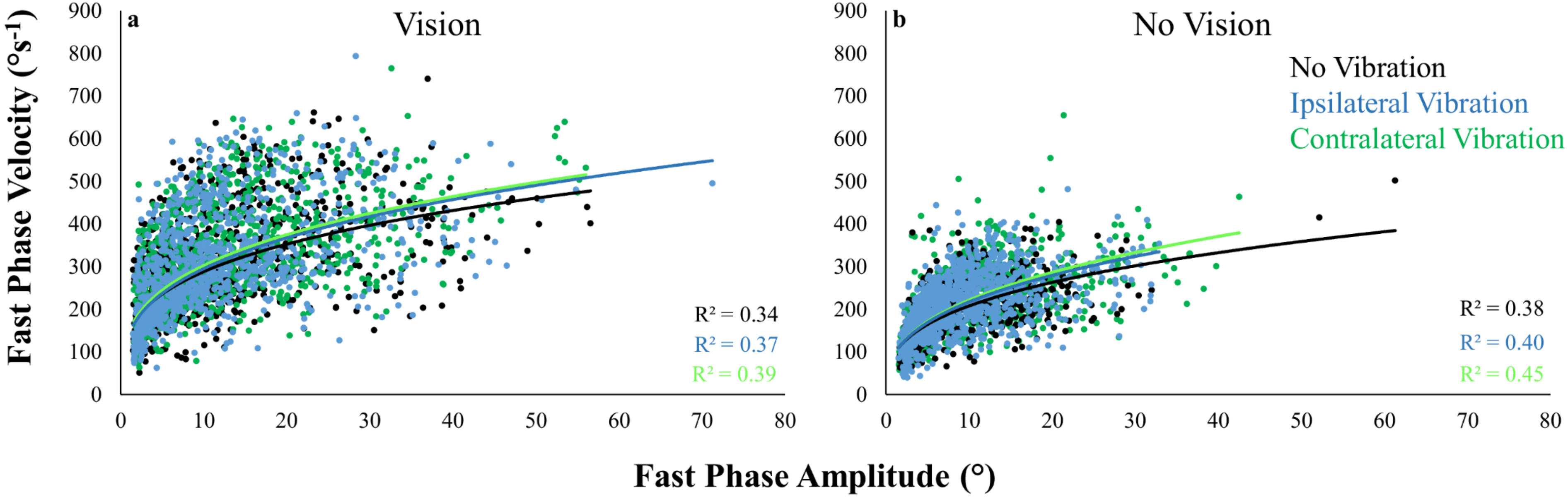

Figure 5-5: Main sequence plots for a) all vision trials and b) all no vision trials.

5.4.6 Stepping characteristics

RM ANOVA analysis found interactions between visual and vibration conditions on stepping frequency ($F_{(2, 22)} = 3.5$, P=.048) and turn duration ($F_{(1.355, 14.900)} = 4.90$, P=.034). Post hoc analysis found that stepping frequency was significantly lower during NVIV than FVIV (P=.016) (Figure 5-6). Pairwise comparisons found significant differences in turn duration between FVIV and FVCV (P=.034), which showed that turn duration was significantly longer in the FVCV condition than the FVIV condition. RM ANCOVA was performed on turn duration and stepping frequency using peak head velocity as a time-varying covariate. The effects of vibration and vision were preserved for stepping frequency but failed to reach significance for turn duration, therefore turn speed can explain the effects of visual and vibration conditions on turn duration, but not on stepping frequency.

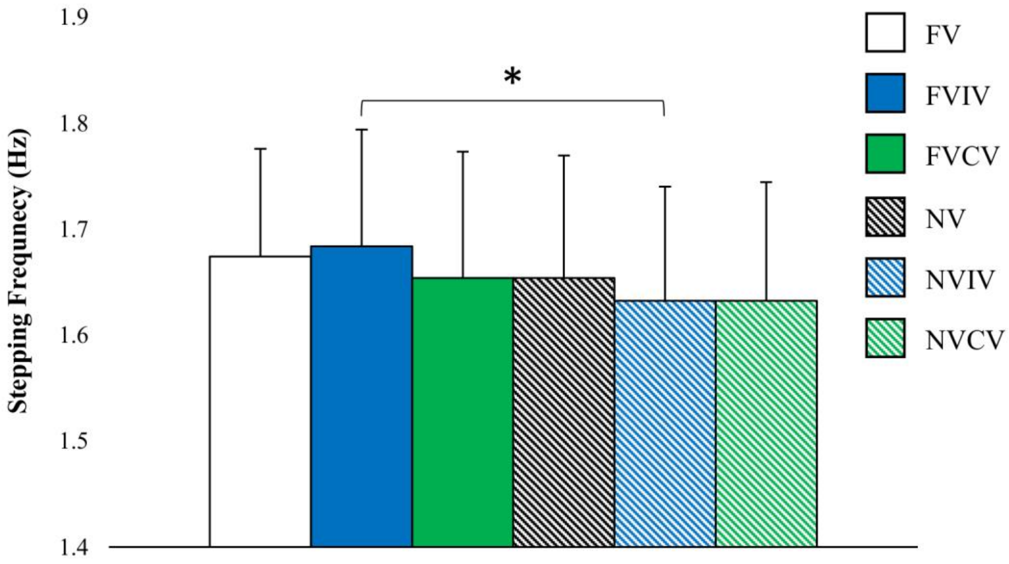

Figure 5-6: There was a significant interaction between visual condition and vibration on stepping frequency which showed that stepping frequency was significantly higher during FVIV than NVIV. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between experimental conditions.

5.4 Discussion

The aim of this study was determine whether proprioceptive input from the sternocleidomastoid was integrated into the mechanism which generates the fast phases during whole-body rotations. Additionally we wanted to see if inaccurate or conflicting proprioceptive information was overridden by visual input, by comparing vibration conditions in both full vision and no vision conditions. During quiet stance and stepping-in-place, there were no systematic effects of vibration on any measured variable. Participants rotated and progressed forward during stepping-in-place both with and without vibration. During turning, we found that vibration of neck muscles *may* facilitate early turn initiation, however, it is likely that the application of vibration and the removal of vision primed attention and thus cued early turn initiation (see next section). Vibration did not cause any significant changes in axial segment coordination, eye movements or stepping behaviour. Lastly, conflicting signals from visual and proprioceptive input *may* have caused enhanced fast phases and increased stepping frequency.

5.4.1 Early turn initiation via sensory priming or attention cues?

During the full vision conditions, both ipsilateral and contralateral vibration caused early reorientation onsets in all segments. There was also a significant interaction between visual and vibration conditions during reorientation, which showed that participants turned earlier during all no vision trials than the FV trials, with no significant differences between onset latencies in the trials with and without vibration. This interaction may have been elicited by the altered sensory information during the preparation of the movement causing an anticipatory or ‘priming’ effect which led to shorter onset latencies. Priming due to proprioception and auditory stimuli have been previously demonstrated during steering responses in driving simulations (Navarro *et al.*, 2007; 2010). When driving a vehicle, maintaining heading while remaining in one lane is necessary to avoid a collision. Lateral control assistance devices are used to give drivers an early warning of a lane departure when the vehicle is about to cross a lane edge line. Methods of lateral control assistance include lateralised sounds from the speakers of the car, haptic assistance, via either symmetrical vibrations of the steering wheel or ‘motor priming’ , asymmetrical oscillations of the steering wheel which move it towards the road centre, in an attempt to activate the wheel correcting response at a proprioceptive level (Navarro *et al.*, 2010). In a set of experiments comparing lateral control warning devices, participants performed driving simulations during distraction tasks. During the distraction tasks, the experiments implemented deviations in the heading of the vehicle, which would then elicit the action of the warning device. They found that any early warning system, irrespective of action, decreases reaction time, however vibration and motor priming were found to have the most significant effect. Compared to the no warning system control condition, vibration decreased reaction times ~70ms during straight route deviations and ~110ms during curved routes; the auditory warning device decreased reactions times only ~20ms in both straight and curved routes. The authors concluded that the profound decrease in the reaction times during wheel vibration was due to its direct action at the sensorimotor level, via elicitation of sensory signals within the effector which performs the motor actions of correcting the steering wheel.

However, it is clear from the results of Navarro *et al.* (2007, 2010) that multiple sensory modalities can elicit similar effects given the same task, suggesting that the change in available sensory information could lead to an attentional shift. It is possible, that by introducing a sensory stimulus (i.e. vibration) or by removing one (i.e. occlusion goggles) that the protocol itself introduced an attentional cue which facilitated earlier turn initiation in the vibration and no vision trials. This has been shown to occur during walking turn using visual cues in stroke patients (Hollands *et al*. 2010a). Stroke patients and healthy aged matched controls performed walking turns to 45° which were visually cued either at the start of the walk, the early cue or pre-planned condition, or at the turn point, the late cue or reactive condition. During the early cue turns, stroke patients reoriented significantly later than controls, however, turn performance was comparable between the two groups during the late cue condition. The authors concluded that external triggering with a light bypassed the impairments in the internal cueing system of the stroke patients, thus allowing more normal turn performance. While our participants did not have any pathology that would limit their ability to use internal cueing, reaction times have been shown to be faster during externally triggered than self-initiated movement in healthy adults (Siegert *et al*. 2002).

5.4.2 Vibration-induced changes in nystagmus characteristics

As this experiment found the same alterations in fast phase characteristics due to vision removal as were found in Chapter 4, only the main effects of vibration and the interactions between visual and vibration conditions on the fast phase characteristics will be discussed.

There was a significant interaction between visual and vibration condition on the peak fast phase velocity which was found to be significantly faster in the ipsilateral vibration condition than the no vibration condition when vision was present, but was significantly slower in the ipsilateral condition than the no vibration condition when vision was removed. Popov *et al.* (1999) showed that unilateral dorsal neck vibration can induce eye movements similar to nystagmus in healthy adults and that the direction of the fast phase is away from the vibration while the slow phase is directed towards the vibration. While the direction of the fast and slow phases did not change from the control conditions and fast phases were always directed towards the turn direction and slow phases were always compensatory, the site of vibration likely has a direct influence on how eye movements will be affected by stimulation. The Popov study stimulated the right and medial aspects of the trapezius, which has ipsiversive action, i.e. contraction of the trapezius causes neck rotation towards the contracted side. Conversely, the sternocleidomastoid has contraversive action and contraction causes neck rotation away from the contracted side. If vibration of a contraversive neck muscle has the opposite action of an ipsiversive muscle, then the expectation would be that vibration induced nystagmus would cause fast phases towards the side of vibration and in fact, we found that fast phases during ipsilateral vibration were significantly larger and faster than those during contralateral vibration. However, this effect only occurred when vision was available and in fact, during no vision trials, fast phases were significantly smaller and slower during ipsilateral vibration. This calls into question as to whether the vibration had any real effect. It would be expected that the effect of enhancing or manipulating proprioceptive input would be more pronounced when visual input was *unavailable* as vision is known to dominate the other senses. Furthermore, the results of the main sequence analysis (Figure 5-5) do not support differences in behaviour due to either visual or vibration conditions. This is not in line with the results of the previous chapter (see Figure 4-5), which show the fast phases elicited in full vision fit the main sequence law, while no vision fast phases are more variable and show decreased adherence to the main sequence law. The results of the current study suggest that fast phases without vision adhere to the main sequence law better than those elicited with vision, although the differences between the two visual conditions are not as stark as those of Chapter 4. Additionally, while the ANOVA results suggest significant differences in fast phase characteristics due to the vibration conditions, this is not apparent in the main sequence plots. Collectively, this suggests that the interaction between visual and vibration conditions on the maximum fast phase amplitude and the peak fast phase velocity may have been spurious results.

5.5 Limitations

While a concerted effort was made to isolate the sternocleidomastoid for muscle spindle stimulation as performed by Bove *et al*. (2002), the lack of an effect on sway measurements, non-systematic rotation and progression during stepping-in-place and the lack of any effects due directly to vibration during turning, it is likely that the vibration was not entirely effective. This could have occurred for several reasons: 1) the vibrators may have not been appropriately placed or not sufficiently taped into place to stay flush with the skin throughout the protocol, 2) the attachment of the vibrators using tape may have prevented normal behaviour and actually hindered normal head-on-trunk movements, 3) the vibrators themselves were not sufficient enough to actually elicit an effect or 4) the participants were simply not sensitive to the vibration. Additionally, if the effects of vibration are long-lasting, it is possible that the inter-trial time (as little as possible due to lab restrictions) used in both the standing/stepping protocol and the turning protocol was insufficient to dampen any possible effects. This could be potentially confounding as the trials were fully randomised, therefore if there were an effect of the vibration, it could still be active during either a no vibration trial or a trial with opposite side vibration. It may be necessary to re-examine the procedures on attaching the vibrators and carefully screen participants for sensitivity to vibration prior to testing to ensure the vibration stimulation is eliciting the desired effect in the muscle spindles. Additionally, the standing/stepping and turning protocols may need to be lengthened in ordered to ensure adequate rest time between trials and potentially limit vibration to one side to prevent any contrary effects.

5.6 Conclusion

Unilateral neck vibration provides signals to the CNS which suggest head on trunk rotation *may* facilitate the release of the steering synergy, however, it is likely that by providing additional sensory information prior to a turn, that attention is primed and increased attention cues early turning. Vibration *may* alters gaze characteristics, indicating potential interactions between neck proprioception and the mechanisms which drive anticipatory eye movements during rotation. These results indicate that neck proprioception *could be* an important source of sensory information during turning and is involved in regulation of the steering synergy, particularly for turn initiation and eye movement control, however, further examination is necessary to support these conclusions.

Chapter 6

The effects of dual-tasking on eye and whole-body coordination during standing turns

6.1 Introduction

Turning is a particularly risky behaviour for some patient populations. Stroke survivors frequently fall while turning (Hyndman, Ashburn and Stack, 2002) and turn-related falls are more likely to result in injury than falls during other behaviours (Cumming and Klineberg, 1994). Parkinson’s patients experience FOG episodes most frequently when turning (Schaafsma *et al.,* 2003) and around a quarter of PD falls are related to freezing events (Michalowska *et al.,* 2005). Studies which have examined turns in stroke patients have found that turning onset is delayed and patients generally take a longer time and use more steps to complete the turn than healthy age-matched control participants, but the sequence and timing of axial reorientation is comparable to controls (Hollands *et al*., 2010a; 2010b). The use of external visual cues during turning protocols have been shown to decrease onset latencies in stroke patients (Hollands *et al.,* 2010b), while the use of auditory cues have been shown to decrease stepping variability in PD patients (Willems et al., 2007). Hollands and co-workers (2010a) hypothesized that the improvements during cued turns may have been due to increasing the focus of attention on the act of turning and that falls which occur during turning may be due to misappropriating limited cognitive resources resulting in motor impairments.

Dual-task paradigms are generally used to assess the extent to which cognition is required to carry out motor tasks (Sheridan *et al.,* 2003). While there are very few studies which have directly performed cognitive dual-tasks while turning, it has been suggested that turning control may require more cognitive involvement than normal straight walking (Takei, Grasso and Berthoz, 1996). An investigation into circular path walking required participants to walk in predetermined circles of various radii while blindfolded during both single-task (walking only) and dual-task (serial subtraction) conditions (Takei *et al.,* 1997). The participants' primary task was to stop after completing two revolutions and align their body with their initial heading. The investigators found that when performing the serial subtraction task while walking, young healthy adults were significantly less able to estimate the total distance walked, the average radius of the trajectory and their initial heading than during the walking only condition (Takei *et al.,* 1997). The authors concluded that generating a trajectory from spatial memory is not an automatic process and requires some attentional control in addition to afferent information about spatial orientation.

Turning capacity is often assessed clinically using the time to turn and number of steps taken as measurements of performance, with longer turn durations and increased step number as indicators of poor performance (Lam and Luttman, 2009). Spildooren and co-workers (2010) investigated turning capacity while dual-tasking in PD patients, using patients who frequently experienced FOG episodes, or 'freezers', disease-severity matched non-freezers and age-matched controls. Participants performed turns while walking, which were either 180° turns back towards the starting position or 360° circles around a marker placed either to the left or right of the walking path, followed by continued straight walking until the end of the walkway. During dual-task conditions, participants were asked to perform the colour classification task which required the participants to respond 'yes' or 'no' to verbally presented colours according to an answering code which changed every trial. They found significant differences between the performance of freezers and non-freezers, which showed that freezers generally turned slower and took more steps than non-freezers. Performance worsened with the addition of dual-task in the freezers, but not the non-freezers or the controls. During dual-tasking freezers actually increased their cadence, whereas both non-freezers and controls decreased their cadence. Overall, their results indicate that cognitive processes influence both gait initiation and ongoing stepping characteristics, specifically in PD patients who experience freezing of gait.

Hollands and colleagues (2014) compared the spatiotemporal stepping characteristics in stroke survivors and healthy older adults during dual-tasking while walking and turning. Participants walked along a pressure sensitive mat and turned either to the right or the left 90° during a single-task turn only condition and during a dual-task condition using serial subtraction. The serial subtraction task required the participants to continuously and verbally subtract 3 from a given number in the 100s. They measured turning capacity in stroke survivors using gait speed, step size, stride time and stride time variability. They found differences in performance between the older adults and stroke patients in the single task, which showed that patients took a longer time to turn, had greater stride variability and spent less time in single support. Interestingly, performance decreased similarly in both groups during the dual-task, highlighting that dual-tasking while turning was difficult for both groups. Importantly, they found that dual-tasking, specifically during turning, increased the amount of time spent in single support, which is inherently unstable due to the small BOS and increases trunk lean towards the inside of the turn (Courtine and Schieppati, 2003b). This suggests that dual-tasking while turning causes adoption of inappropriate and potentially hazardous stepping strategies that may lead to increased fall-risk in both older adults and stroke patients.

In addition to gait initiation and stepping deficits during turns experienced by PD patients, it has been suggested that turning impairments may relate to deficits in oculomotor behaviour (Lohnes and Earhart, 2011; 2012). A strong link between eye and stepping behaviour has been demonstrated during turning (Anastasopoulos *et al.,* 2009) and eye movement suppression results in significant disruptions in axial segment coordination (Reed-Jones *et al.*, 2009a; 2009b; Ambati *et al.*, 2013) and delayed gait initiation as demonstrated in Chapter 4. If eye movements are directly related to gait initiation, and dual-tasks increase gait onset latencies in older adults, PD and stroke patients and increase the number of FOG episodes in PD patients, it stands to reason that eye movements may also be affected by the addition of a cognitive task while turning. However, during turning, there is stereotyped oculomotor behaviour, and it has been suggested that the fast phases of turning nystagmus are mediated via the same structures which elicit saccadic eye movements (Ron, Robinson and Skavenski, 1972) meaning that nystagmus phase fast phases are elicited via subcortical mechanisms and are part of an automatic process which is not affected by cognition. However, there is growing evidence which suggests that areas which direct eye movements and areas which process attention, specifically visual attention, have overlapping neural structures (Corbetta *et al.,* 1998). Differences in brain activity were studied using functional magnetic resonance imaging (fMRI) between covert shifts of attention (i.e. without eye movements) and overt shifts of attention (i.e. saccadic movement to stimuli). They found activation in the same cortical areas during both covert and overt shifts of attention, suggesting that attentional areas, specifically visual attention and oculomotor processes are tightly integrated. However, the task used by Corbetta and colleagues was specifically using voluntary saccades and saccades represent a diverse population of eye movements with many different proposed brain areas of involvement (Walker *et al.,* 2000). In a series of dual-task interference experiments involving reflexive, voluntary and anti-saccades, the authors demonstrated that saccades which were directed via cortical brain areas were delayed by dual-task interference while eye movements directed by subcortical brain areas were not affected by the addition of a dual-task (Pashler, Carrier and Hoffman, 1993). Yardley and colleagues (1999) investigated whether perception of self-motion and spatial orientation was registered subcortically using a dual-task paradigm. They passively rotated participants in a motorised chair in darkness and measured their ability to accurately return to their starting position (via a joystick which moved the chair). They performed this task during a free gaze condition, a fixed gaze condition and under a free gaze dual-task condition where they measured participant reaction times to an auditory stimulus. While they only measured spatial perception during the free gaze conditions, which worsened with the addition of a dual-task, they did find that participants' poorest performance on the secondary task was during the fixed gaze condition. The authors concluded that a significant degree of attention is required to accurately monitor self-motion and that cognitive effort is necessary to suppress reflexive eye movements due to the VOR. This raises questions as to whether the effect of eye movement suppression on subsequent kinematics is due to the lack of eye movements per se, or whether the increased cognitive load causes the disruptions in coordination or whether alterations in behaviour are due to the specific cognitive processes involved in VOR suppression. Changes in the goal during turns has been shown to effect the onset of segmental reorientation (Anastasopoulos *et al.*, 2009). During turns to unpredictable targets, there is a clear top-down reorientation sequence which begins with the eyes, followed by the head, trunk and then the feet. Segment reorientation during predictable trials is simultaneous and the sequence of reorientation is variable. With the exception of the initiating saccade, nystagmus characteristics were consistent between the predictable and unpredictable trials. This could suggest that a different mechanism is used when turning is performed in concert with the task of searching for the target. Collectively, the findings of these studies lead to the question: does performing a secondary cognitive task during turning lead to altered eye movement behaviour? And if so, do changes in eye movements lead to subsequent changes in intersegmental coordination and stepping behaviour?

The aim of the current study was to determine the effect of increased cognitive effort in young healthy individuals on oculomotor and whole-body coordination during standing turns. Our objectives were to: a) compare the overall spatiotemporal coordination between single-task turns and during turns with a concurrent cognitive task, b) compare the stepping behaviour between the single and dual-task conditions and c) determine whether increased cognitive effort causes a change in oculomotor behaviour while turning. We specifically predicted that: i) whole-body coordination characteristics would remain stable between single-task and dual-task turns, but that the addition of a secondary task would cause a delay in turning onset, ii) stepping characteristics might be affected by addition of a secondary task and iii) that eye movement characteristics will be substantially similar between single- and dual-task conditions.

6.2 Methods

6.2.1 Participants

Fourteen healthy young adults, mean age 21.54 years (± 1.47 *SD*) volunteered for the study. The experimental protocol was approved by the Liverpool John Moores Research Ethics committee (REC) and all participants gave written and informed consent. Participants were excluded if they reported neurological, musculoskeletal, or cognitive impairments, or if taking medication for anxiety and/or dizziness or used an assistive walking device. Cognitive function was tested using the MMSE, where a score of 26 of above indicates intact cognitive function (Folstein, Folstein and McHugh, 1975). Additional cognitive testing was assessed using the Trail Making Test parts A and B; a completion time of ≥78 seconds and ≥273 seconds, respectively, indicate deficient cognitive function (Reitan, 1958). Visual testing was performed using the Freiburg Vision Test (FrACT) and included an examination for monocular and binocular visual acuity using the Landolt C test (Bach, 1996). All participants had normal or corrected to normal visual acuity (20/20 or better).

6.2.2 Protocol

Turns were performed to 180° to either the left or the right in either a single-task turn only (TO) condition or during a dual-task condition using a serial subtraction (SS) task which was performed during the execution of the turn task. For the SS task, a number between 125-250 was presented on the screen to the participant concurrently with the auditory go cue; the participant was required to continuously subtract ‘3’ from this number while concurrently turning. As facial muscle movement interrupts EOG signal, the serial subtraction was performed silently and the answer was stated to the investigator at the end of the trial. During the experiment the two sets of lights nearest to the screen were turned off in order to increase visibility of the turn demonstration and subtraction number videos. Trial order was fully randomised for each participant. A total of 10 trials were recorded for each condition for a total of 40 trials.

6.2.3 Data collection

Each experimental session was filmed to confirm the serial subtraction task results.

6.2.4 Data analysis

Cognitive tasks. Performance on serial subtraction was considered accurate if the participant’s answer was any correct subtraction of three from the given number. The frequency of correct answers, incorrect answers and percentage correct were determined for each participant.

6.2.5 Statistical analysis

The statistical package SPSS (22.0) was used for all statistical procedures. A 2 x 2 RM ANOVA was performed on all dependent variables with direction (left or right) and cognitive condition (TO or SS) as repeated measures factors. No effects of turn direction (left versus right) were found and data was collapsed; therefore the presented results are from a paired T-test design. RM ANCOVA was subsequently performed on significant results to control for turn speed using peak head velocity as a time-varying covariate. Pearson’s Product moment correlation was used to determine the strength of relationships between the dependent variables. Main sequence analysis was performed on fast phase data for all experimental conditions; correlation coefficients were then compared using a Fisher transformation. Frequency distribution analysis was performed on all fast phase characteristics and Kolmogorov-Smirnov Z was run to determine differences between the distributions from each experimental condition. All mean values are presented with standard deviations unless otherwise stated. Statistical significance was set at $P<.05$. A Bonferroni’s correction was used for multiple comparisons.

6.3 Results

6.3.1 Serial subtraction results

Participant serial subtraction accuracy ranged from 50 to 95% correct responses. Group mean serial subtraction correct response rate was 81.43 ±12.92%.

6.3.2 Segment onset latencies

Segment reorientation began with the head followed by the thorax and pelvis, then the eye and leading foot and then the trailing foot (Figure 6-1). However, the onsets of the axial segments were not significantly different from one another nor were the eye and leading foot for either condition. Pearson's product moment correlation analysis revealed highly significant correlations between the onset latencies of all segments (Table 6-1). Paired T-tests were performed on each segment onset latency and found significant differences in onset between TO and SS conditions in all segment latencies (eye: $t_{(13)} = -2.86$, $P=.014$; head: $t_{(13)} = -2.47$, $P=.028$; thorax: $t_{(13)} = -2.9$, $P=.012$; pelvis: $t_{(13)} = -2.59$, $P=.022$; leading foot: $t_{(13)} = -2.82$, $P=.014$; trailing foot: $t_{(13)} = -3.32$, $P=.005$). Onset latencies were shorter during TO trials than SS trials for all segments (Table 6-1). To determine whether the difference in onset latencies between conditions were due to changes in speed, RM ANCOVA was performed on all segment onset latencies. The effects of dual-tasking were preserved when peak head yaw velocity was added as a covariate demonstrating that turning speed cannot explain differences found between TO and SS.

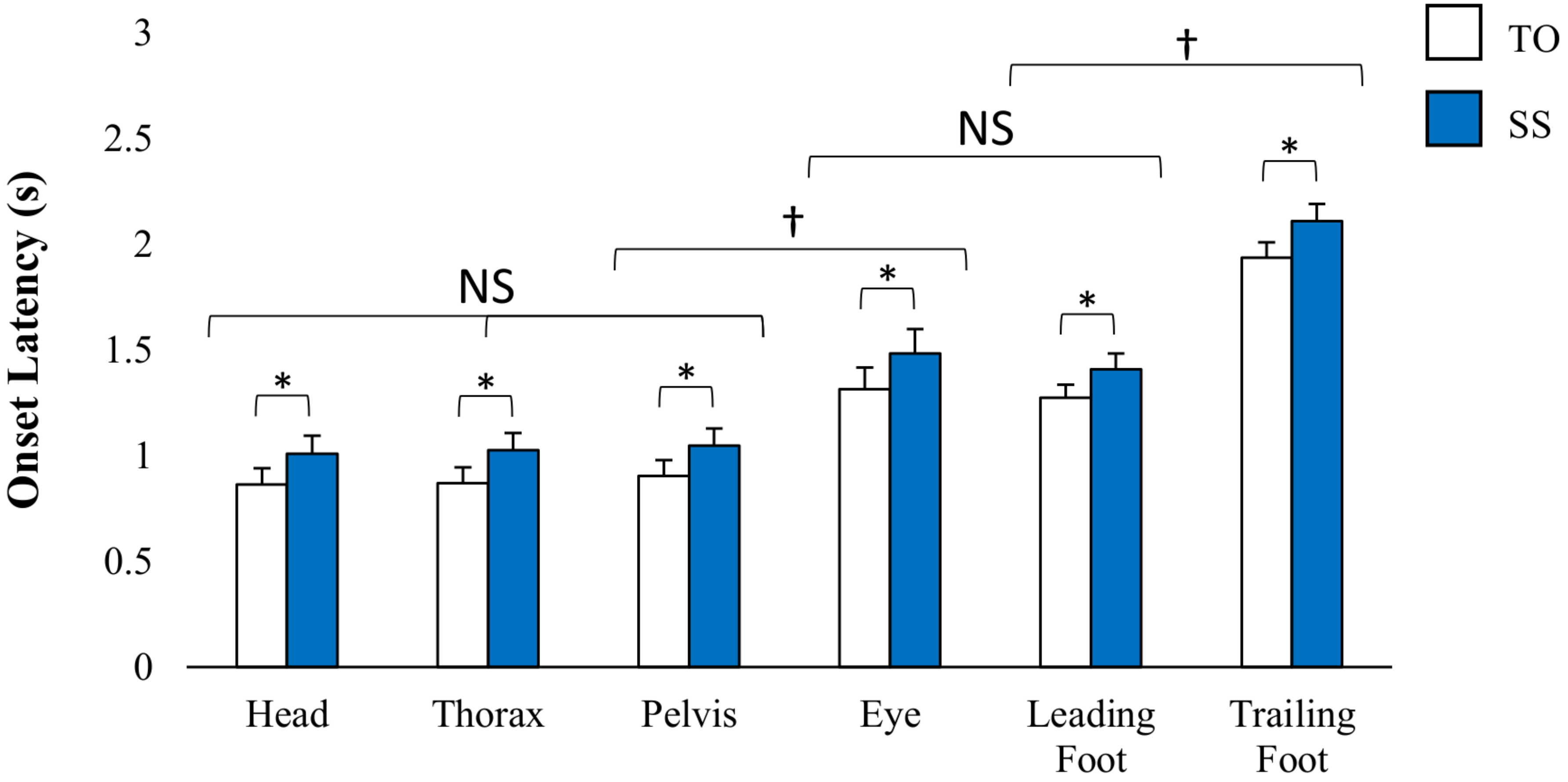

Figure 6-1: Mean onset latencies for all segments in all experimental conditions. All segment onset latencies were significantly later in the SS condition than TO onsets. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between experimental conditions and brackets with daggers represent statistically significant differences between segments.

Table 6-1a

Mean onset latencies (ms) for all participants during the turn only condition and results of Pearson's product moment correlation (R^2) between the onset latencies of the eye, axial body segments and foot rotation from all participants from all turn only trials.

	Control		Eye	Head	Thorax	Pelvis	Leading Foot	Trailing Foot
Eye	1312 ± 300	Pearson correlation		0.40	0.36	0.43	0.32	0.36
		Sig. (2-tailed)		<.001	<.001	<.001	<.001	<.001
Head	864 ± 189	Pearson correlation	0.40		0.76	0.62	0.57	0.48
		Sig. (2-tailed)	<.001		<.001	<.001	<.001	<.001
Thorax	870 ± 185	Pearson correlation	0.36	0.76		0.75	0.61	0.48
		Sig. (2-tailed)	<.001	<.001		<.001	<.001	<.001
Pelvis	905 ± 180	Pearson correlation	0.43	0.62	0.75		0.62	0.47
		Sig. (2-tailed)	<.001	<.001	<.001		<.001	<.001
Leading Foot	1275 ± 162	Pearson correlation	0.32	0.57	0.61	0.62		0.79
		Sig. (2-tailed)	<.001	<.001	<.001	<.001		<.001
Trailing Foot	1935 ± 220	Pearson correlation	0.36	0.48	0.48	0.47	0.79	
		Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	

$N = 272$

Table 6-1b

Mean onset latencies (ms) for all participants during the serial subtraction condition and results of Pearson's product moment correlation (R^2) between the onset latencies of the eye, axial body segments and foot rotation from all participants from all serial subtraction trials.

	Subtraction		Eye	Head	Thorax	Pelvis	Leading Foot	Trailing Foot
Eye	1485 ± 286	Pearson correlation		0.38	0.37	0.34	0.28	0.29
		Sig. (2-tailed)		<.001	<.001	<.001	<.001	<.001
Head	1008 ± 220	Pearson correlation	0.38		0.87	0.79	0.64	0.53
		Sig. (2-tailed)	<.001		<.001	<.001	<.001	<.001
Thorax	1025 ± 204	Pearson correlation	0.37	0.87		0.86	0.66	0.52
		Sig. (2-tailed)	<.001	<.001		<.001	<.001	<.001
Pelvis	1047 ± 194	Pearson correlation	0.34	0.79	0.86		0.68	0.51
		Sig. (2-tailed)	<.001	<.001	<.001		<.001	<.001
Leading Foot	1406 ± 207	Pearson correlation	0.28	0.64	0.66	0.68		0.78
		Sig. (2-tailed)	<.001	<.001	<.001	<.001		<.001
Trailing Foot	2108 ± 242	Pearson correlation	0.29	0.53	0.52	0.51	0.78	
		Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	

N = 275

6.3.3 Intersegmental relationships

Paired T-tests found no significant differences between TO and SS in peak head-thorax separation (*P*=.782) and peak head-pelvis angular separation (*P*=.785). Pearson correlation analysis was performed between peak head velocity and peak head-pelvis angular separations, which revealed significant but weak relationships between peak head velocity and peak head-pelvis separation in the TO condition (R = .37, *P*<.001) and SS condition (R = .15, *P*=.016).

6.3.4 Fast phase characteristics

Paired T-tests were performed on fast phase characteristics and found significant differences between conditions in the peak fast phase velocity ($t_{(13)} = 4.49$, *P*=.001), which showed that peak fast phase velocity was significantly faster during the TO (414.77 ± 74.46°s^{-1}) condition than the SS (383.78 ± 66.92°s^{-1}) condition. RM ANCOVA was performed on peak fast phase velocity to control for turn speed, however, the effects of dual-tasking were preserved demonstrating that turning speed cannot explain differences found between TO and SS. There were no significant differences in the NFPF between conditions.

Main sequence analysis found no significant differences in the relationship between fast phase amplitude and fast phase velocity between the turn only and serial task subtraction fast phases (Figure 6-2).

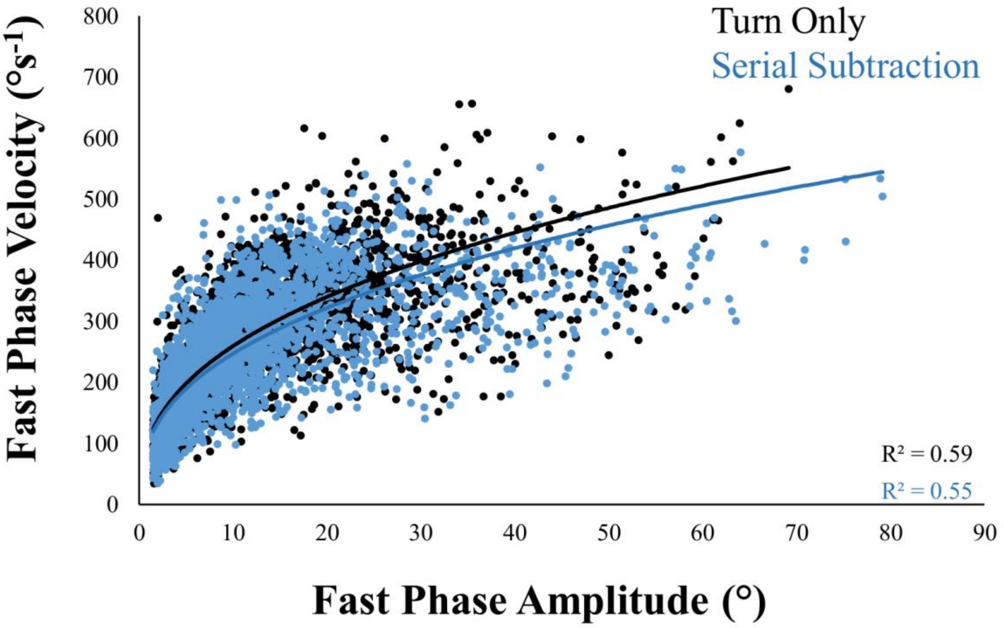

Figure 6-2: Main sequence plots for turn only and serial subtraction fast phases.

Frequency distribution analysis was performed on the eye-in-orbit position at the beginning and end of each fast phase and the fast phase amplitudes and velocities for all fast phases elicited. To determine differences between the distributions, two-sample Kolmogorov-Smirnov tests were performed between the conditions. There were no significant differences found between the distributions for any of the dependent variables.

6.3.5 Stepping characteristics

Paired T-tests were performed on the spatiotemporal stepping characteristics of the leading and trailing steps. Significant differences between TO and SS conditions were found in the leading step acceleration ($t_{(13)} = 2.23$, $P=.044$) and the stepping frequency ($t_{(13)} = 5.36$, $P<.001$). Leading step acceleration was significantly higher in the TO condition than the SS and stepping frequency was significantly lower during the SS condition than the TO condition (Figure 6-3). Paired T-tests on turn duration found turns during SS (4.74 ± .45s) took significantly longer ($t_{(13)} = 2.23$, P=.044) than the TO condition (4.47 ± .47s).

RM ANCOVA was performed on leading step acceleration, stepping frequency and turn duration using peak head velocity as a time-varying covariate. The effects of dual-tasking were preserved on leading step acceleration, but failed to reach significance on stepping frequency and turn duration demonstrating that while turn speed cannot explain the differences found between conditions in leading step acceleration, turn speed can explain differences between conditions for stepping frequency and turn duration.

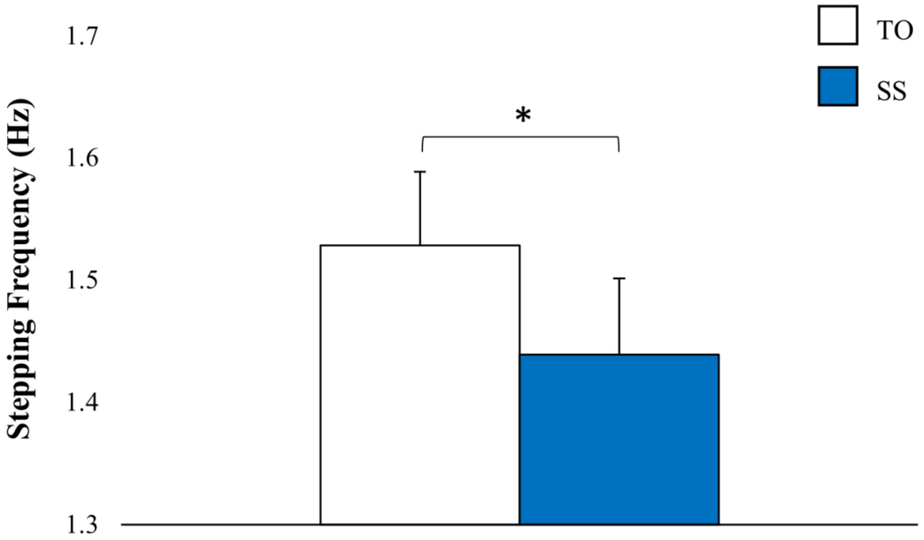

Figure 6-3: Mean stepping frequency. There was a significant decrease in stepping frequency during the SS condition compared to the TO condition. Error bars represent 95% confidence intervals, brackets with asterisks represent statistically significant differences between experimental conditions.

6.4 Discussion

This was the first study to explore how nystagmus characteristics during whole-body rotation are influenced by the addition of a cognitive task. The aim was to determine whether dual-tasking while turning caused the adoption of another oculomotor strategy which subsequently influenced kinematics and specifically stepping behaviour. We found that while performing a secondary-task while turning, young healthy adults delay turn initiation and turn slower, however, there was no difference in eye movement behaviour between single- and dual-task turns, intersegmental coordination was unaffected and there were no changes in stepping behaviour aside from a reduced stepping frequency.

6.4.1 Dual-tasking delays movement onset but overall kinematics are preserved

We found similar delays in all segment onsets at reorientation during the serial subtraction task compared to the control condition, suggesting that turning or at least eliciting a turn requires some attentional control. Most studies perform dual-tasking during ongoing movement and measure the reaction time of the cognitive task, rather than the onset of motor activity, however, as our protocol began both the single and dual-task at the same time, and there was a clear interaction between attention and movement onset, it seems appropriate to compare onset latencies with reaction times during other dual-task studies. Lajoie *et al.* (1993) compared the attentional requirements for increasingly demanding postural tasks by performing an auditory response task during sitting, standing and walking. They found that reaction times increased with increased balance requirements, suggesting that motor task difficulty directly affects the amount of cognition required for performance, in line with the findings of Takei *et al.* (1997) who suggested that turning was more cognitively demanding than straight walking. Another group found conflicting results suggesting that attentional demands were not different between tasks of differing levels of difficulty (Abernethy, Hanna and Plooy, 2002). They investigated the attentional demands of treadmill gait during transitions from walking to running at multiple speeds using an auditory reaction time test. While they did find increased reaction times during treadmill locomotion dual-tasking compared to lone auditory task performance, they found no significant differences between the dual-task reaction time during different gait speed transitions. A similar study found delays in reaction times on a secondary task during treadmill walking, however increasing the difficulty of the secondary task did not influence reaction time (Regnaux *et al.*, 2006). These findings suggest that locomotor activity may require some attentional control, but it is limited and increasing the difficulty of a specific secondary task does not require increased attentional resources. However, it is likely that during natural locomotion when attentional demands can be numerous, that these delays in reaction times could have a compounding effect.

Comparisons of the intersegmental coordination of the participants from the current study with previous studies on turning and dual-tasking is not possible as there are only a few studies available and none of these studies have investigated intersegmental coordination. Direct comparisons between our participants in the two conditions show that all temporal measurements were delayed in the serial subtraction condition due to the initial delay of movement onset, however spatial characteristics were comparable between conditions. There are turning studies which have compared pre-planned and cued conditions, which require a level of attention to react and adapt locomotion for turning (Hollands *et al.*, 2010b). While it appears that cued turning actually decreases turning onset latency, as opposed to the delaying it, the sequence of segment reorientation is consistent between planned and cued turns. The authors proposed that differences between cued and non-cued conditions, specifically in stroke survivors, may indicate an impairment in gait initiation. If this is the case, divided attention potentially interferes with the Basal Ganglia (BG) pathways involved in the initiation of movement (Denny-Brown, and Yanagisawa, 1976; Hauber, 1998). PD patients, who have neurodegeneration specifically in the BG, have difficulty with dual-tasking, which often results in FOG episodes (Giladi and Hausdorff, 2006; Spildooren *et al.*, 2010).

6.4.2 Turning nystagmus is mediated subcortically

This is the first study to directly look at turning nystagmus during the simultaneous performance of a cognitive task. There were no significant differences between any of the measured fast phase characteristics between conditions with the exception of the peak fast phase velocity, which was found to be significantly faster in the single-task turn only condition ($414.77 \pm 74.46°s^{-1}$) than during the dual-task serial subtraction condition ($383.78 \pm 66.92°s^{-1}$). This result cannot be explained by differences in turn speed as demonstrated by the RM ANCOVA results, which showed that the effects of dual-tasking were preserved when using peak head velocity as a covariate. Peak head yaw acceleration was slightly, but not significantly higher during the TO condition than the SS condition, however, if the level of stimulation in the SCCs directly influences the signals which generates the fast phases, it is possible that slightly faster head yaw velocity could lead to larger signal generation for the fast phase. However, as there were no differences found between the main sequence relationships or the distributions of any of the fast phase characteristics between the single and dual-task conditions, it is unlikely that this finding was due to divided attention. Overall, our findings support the idea that the fast phase eye movements of turning nystagmus are mediated via subcortical mechanisms and represent an automatic feed forward process.

6.4.3 Stepping frequency is modified by divided attention

We found the same altered stepping behaviour in response to the addition of a cognitive dual-task while turning as has been demonstrated in healthy older adults and non-freezing PD patients (Spildooren *et al.,* 2010), which is that divided attention causes a decrease in the rate of stepping. However, we did not find any differences between the conditions in either leading foot step duration (*P*=.966) or trailing foot step duration (*P*=.617) and we did find that participants took significantly longer to turn while performing serial subtractions than when turning alone, likely a direct consequence of the reduced stepping frequency. As we incorporated a turn speed control phase at the beginning of the experiment (described in section 2.2) which all participants successfully completed, it appears that the adoption of the decreased stepping frequency and the resulting increased turn time may indicate a posture first strategy (Bloem *et al.,* 2006). Differences in the prioritisation of the motor versus the cognitive component of a dual-task can be measured using the Multiple Tasks Test (MTT) (Bloem *et al.,* 2001). This test was designed so that multiple concurrent and increasingly demanding postural and cognitive tasks which represent everyday situations could be evaluated in terms of cognitive and motor errors, defined by hesitation or cessation of task performance. A participant who prioritised the motor performance (i.e. fewer errors during postural tasks than cognitive tasks) over the cognitive performance was considered to adopt a ‘posture first’ strategy, while participants who prioritise cognitive performance adopt a ‘posture’ second strategy. Utilisation of the MTT has shown that healthy younger and older adults generally use a posture first strategy, while PD patients tend to use a ‘posture second’ strategy (Bloem *et al.,* 2001; 2006). Additionally, the specific direction of altered stepping frequency (i.e. increased or decreased) in response to a cognitive task may be indicative of the adopted postural strategy. While the decrease in stepping frequency was clear in our group results, observation of individual participants found one participant who actually increased stepping frequency, albeit slightly, from the TO condition (1.39 ± 0.06Hz) to the SS condition (1.41 ± 0.10Hz) during left turns. While these differences were slight, it may be worthwhile to look at dual-task related changes in stepping frequency at an individual level in addition to a group level.

6.5 Conclusion

Divided attention during dual-tasking leads to delays in turn initiation and a reduction in stepping frequency, leading to longer turn durations. However, eye movement characteristics and intersegmental coordination parameters are unaffected by the addition of a secondary task during turns. These results support the notion that turning is automatic and subcortically controlled, but cognition is important for other aspects of turning such as movement initiation.

Chapter 7

General Discussion

The rationale for this work in this thesis was based on a collection of previous experiments which found altered turning kinematics with changes in turn parameters (Hollands, Ziavra and Bronstein, 2004; Anastasopoulos *et al.*, 2009; Sklavos, Anastasopoulos and Bronstein, 2010), altered steering synergies with restrictions on eye movements (Reed-Jones *et al.*, 2009a*;* 2009b) and potentially pathological differences in oculomotor behaviour while turning (Lohnes and Earhart, 2011; 2012). It was our intention to perform a detailed investigation into oculomotor behaviour and whole-body coordination during standing turns and how these parameters are affected by turn-context, perturbations of the visual and proprioceptive systems and the influence of cognition.

7.1 Segmental reorientation

Throughout the four studies described in this thesis, participants demonstrated a relatively *en bloc* onset of axial rotation (see Figure 3-2[1]), whereby the onset latencies of the individual axial segments did not differ significantly from one another. This was followed by eye reorientation towards the turn direction and then the stepping of the leading and trailing feet. This was different to the expected top-down reorientation usually demonstrated in young healthy people (Hollands, Ziavra and Bronstein, 2004; Anastasopoulos *et al*., 2009). *En bloc* rotation has largely been deemed a pathological strategy as PD (Vaugoyeau *et al.*, 2006; Crenna *et al.*, 2007; Huxham *et al.*, 2008) and stroke patients (Lamontagne and Fung, 2009) have been shown to use this strategy. However, both PD (Anastasopoulos *et al.*, 2011) and stroke patients (Hollands *et al.*, 2010a, 2010b) have also been shown to use the normotypical top-down reorientation strategy. These contrasting results demonstrate the need to re-evaluate the criteria which are used to determine the onset of rotation, as measurement varies greatly between studies. Some studies have used amplitude (Akram, Frank and Fraser, 2010) or velocity (Crenna *et al.*, 2007) thresholds and some have used the time at which the segment displacement exceeds a certain number of standard deviations outside the mean of the control parameter, whether it is walking (Hollands *et al.*, 2010a; 2010b) or standing posture (Ashburn *et al.*, 2014).

Turn context also needs to be taken into consideration when determining whether behaviour is considered normal or pathological. Our participants, who were all healthy young individuals between the ages of 18-30, were required to make turns to spatially predictable locations which were not marked i.e. there were no targets indicating where 45°, 90°, 135° or 180° were located relative to the screen at 0°. We found, with few exceptions, that either the head or an *en bloc* rotation of the axial segments initiated the turn followed by eye rotation. Ashburn *et al.* (2014) investigated standing 180° turns using a protocol similar to our own. Participants stood facing a red light and were cued to begin turning when the light extinguished. They found that their participants, healthy adults and PD patients both used the same sequence of reorientation starting with the head, rather than the eye. The works of Anastasopoulos *et al.* (2009, 2011) have investigated segment reorientation using both predictable and unpredictable turn locations. Participants were observed while turning towards a lit LED positioned at either ±45°, ±90°, ±135° or 180°, however at turn onset for turn amplitudes outside the field of view, they were unaware which LED was lit and therefore were required to search for it while turning. Participants were measured during both outbound trials, to the unpredictable LED locations and during inbound trials where they turned to the spatially predictable starting position located at 0°. The investigators found that during unpredictable trials, there was a clear top-down organisation of reorientation beginning with the eyes, followed by the head, trunk and then the stepping of the feet. However, during predictable trials, head reorientation occasionally preceded eye movement and sometimes trunk latencies were shorter than head latencies, indicative of an *en bloc* turning strategy. Comparisons of PD patients with controls using this protocol found that patient behaviour was not significantly different from controls i.e. top-down segmental onset sequence in unpredictable trials and *en bloc* turning in predictable trials. The collective results of the experiments described in this thesis and the works of Ashburn *et al.* (2014) and Anastasopoulos *et al.* (2009, 2011) suggest that spatially predictable standing turns do not necessarily begin using an initial saccade, and that spatially unpredictable standing turns require initial gaze shifts, which likely facilitate a visual search strategy when the task goal is locating a target.

7.2 Intersegmental coordination

Our first study, which manipulated turn parameters showed systematic effects on the relationships between the segments which vary with both turn amplitude and turn speed. As previously discussed, our participants initiated turns *en bloc*, however observation of the data showed that the head rotated faster than either the thorax or pelvis and the head anticipated the trajectory of the lower segments throughout most of the turn. Akram *et al.* (2010b) examined older adults making 90° turns and found that older adults initiated turns in an *en bloc* manner, but the head turned faster than the other segments and this behaviour occurred in both eyes-open and eyes-closed conditions. While they noted that the head rotated much further ahead in the eyes-open condition than the eyes-closed condition, they did not measure this difference. We chose to measure how much the head spatially anticipated the lower axial segments by measuring the peak of the head-thorax and head-pelvis curves which describe the motion of the head relative to the lower segment. We found that the peak separation between the head and lower segments increased with increased turn amplitude and further increased with increased turn speed; however differences between turns to 135° and 180° were negligible. Additionally, we found the extent of head-body separation varied as a function of turn speed (Figure 3-5). From these results, we suggest that the determination of *en bloc* turning using the relative axial rotation throughout the turn is more appropriate than a criterion based on measures of reorientation onsets, which are clearly not predictive of subsequent turn behaviour. Solomon *et al.* (2006) used comparisons of simultaneous head-in-space velocity with pelvis-in-space velocity to determine *en bloc* portions of the standing turns to 90°. They designated three categories: 1) head-on-pelvis rotation, defined by head-in-space velocity at least $10°s^{-1}$ greater than pelvis-in-space velocity, 2) *en bloc*, defined as head-in-space velocities and pelvis-in-space velocities within $10°s^{-1}$ of each other and 3) head stabilised, defined as head-in-space velocity at least $10°s^{-1}$ less than pelvis-in-space velocity. They found a general pattern, where the early portion of the turn was predominated by head-on-pelvis rotation, the mid portion of the turn was largely *en bloc* and the end of the turn was head stabilised. They likened this strategy to an eye nystagmus pattern. Measurements such as that of Solomon *et al.* (2006) or the peak segment separations should be used when determining overall turning behaviour, specifically in diagnosis of turning deficits in clinical populations where defining the extent of segmental independence during turning may inform their subsequent therapy.

7.3 Turning nystagmus

Each of our studies has demonstrated that nystagmus eye movements are an intrinsic part of the mechanism which generates turning behaviour. Our first study demonstrated that not only does altering turn parameters affect kinematics, but there are systematic changes in the characteristics of the fast phases of nystagmus, specifically that fast phase amplitude and velocity increases with increasing turn speed and that increasing turn duration via either increased turn amplitude or decreased turn speed elicits more fast phases. Such context-dependent changes become increasingly important when making comparisons between clinical populations and aged-matched healthy adults. It is well known that certain clinical populations have difficulty performing turns and this is demonstrated by slower turn speeds and thus longer turn durations. The aged-matched counterparts of these clinical patients inevitably turn faster and quicker. Subsequently, the faster turns of the healthy adults are compared with the slower turns of the patients and usually any conclusions drawn point to a pathological cause for all differences. However, by comparing slower and faster turns in the same healthy participants, we have shown that by simply changing the turn speed, nearly all fast phase characteristics were altered. This means that there is a need to take into account differences in turn speed when making clinical comparisons or by comparing speed-matched turns to elucidate the differences which are directly due to pathology and not to behaviour.

Our second study, which directly manipulated both visual input and eye movements demonstrated the robust anticipatory nature of nystagmus as fast phases clearly led the way during the majority of the turns in both full vision and no vision conditions, which is in line with previous work (Grasso *et al.*, 1998; Authié *et al.*, 2015). While fast phase characteristics were slightly modified when vision was not available i.e. small amplitudes and slower velocities, this was likely due to the lack of optokinetic stimulation that is normally present during head rotations with available visual input. The results of vision removal were in striking contrast to the results of the gaze fixation condition which required participants to suppress eye movements throughout the turn. During gaze fixation, there were significant delays in the onset of both feet and the stepping frequency was significantly reduced compared to full vision and no vision conditions. We used fixation to suppress eye movements as that has been demonstrated to successfully suppress nystagmus characteristics during passive whole-body sinusoidal rotations, but only when fixating a target (Schmid, Zambarbieri and Magenes, 1981). The flocculus region of the cerebellum has been identified as responsible for fixation-induced suppression of the VOR during passive rotation, as the activation of Purkinje cells in this region significantly reduces when a visual target is removed during gaze fixation. It is likely that this oculomotor-cerebellar mechanism is involved in stepping behaviour as cerebellar patients have demonstrable oculomotor and locomotor deficits during precision walking tasks, including hypometric saccades and alteration in temporal aspects of the gait cycle (Crowdy *et al.*, 2000). Stepping errors are reduced in cerebellar patients when they ‘rehearse’ the eye movements required for successful performance prior to performing a precision stepping task (Crowdy *et al.*, 2002).

The results of Chapter 5 found that during turns with neck vibration ipsilateral to the turn direction, peak fast phase velocity was faster than both no vibration and contralateral vibration turns when vision was present. This could suggests that the mechanism that generates fast phases integrates information sent from neck proprioceptors, specifically when the signal sent about head rotation is inconsistent with the direction of motion, e.g. during a left-directed turn, vibration of the left sternocleidomastoid stimulates the muscle spindles and elicits a signal to the CNS indicating head rotation towards the right, which would be inconsistent with information from the visual and vestibular systems, as well as proprioceptors located throughout the trunk. However, as no main effects of vibration alone were found and the results of the main sequence analysis were not in line with the results of either Chapter 3 or Chapter 4, it is likely that this finding was not in fact a true interaction between the visual and vibration conditions. This is likely as the main sequence analysis from Chapter 4 suggests that fast phases which occur without visual input are significantly less in line with the main sequence law than those elicited during vision. Similar findings have been shown when performing main sequence analyses on optokinetic nystagmus (OKN) and optokinetic after nystagmus (OKAN), which show that OKN, which is elicited only when visual input is available, has higher peak velocities for similar amplitude fast phases than OKAN which is elicited *following* visually-induced OKN (i.e. the nystagmus continues in darkness once the visual stimulus has been removed) (Kaminiarz, König and Bremmer, 2009). Meanwhile, the results of Chapter 5 suggested that there were no significant differences between fast phases elicited in full vision and no vision and the main sequence analysis did not reveal any differences between vibration conditions which would support the interaction found from the RM ANOVA While the results of Chapter 5 are inconclusive, it is clear that proprioception, specifically neck proprioception, is an important source of sensory information as VOR gain is significantly during active head rotation than during passive head rotation (Barnes *et al*., 1985). Additionally it is clear that vibration of neck muscles can induce effects on the eye movement, as vestibular patients, who upregulate the COR to replace the VOR generated compensatory eye movements, sometimes generate nystagmus-like eye movements upon the application of neck vibration (Ohki *et al.*, 2003).

7.4 Step coordination

In experiment 1, we aimed to determine how stepping behaviour is altered during changes in turn context, e.g. does one increase step size or make more steps to achieve larger turn amplitudes? We expected we would see systematic changes in stepping behaviour as a function of both turn amplitude and turn speed, as we did with intersegmental coordination, however stepping characteristics appear to be modulated similarly during all turn amplitudes. We measured the spatial and temporal characteristics of the leading and trailing steps for comparison as participants frequently only used two steps to reach the smaller amplitudes. The leading step size was smaller during turns made to 45°, but leading step size did not differ between the larger amplitude turns and there were no significant differences in leading step size due to speed. Trailing step size did increase with increasing amplitude, but there were no differences between trailing step size to 135° or 180°. Step duration was slightly shorter during leading steps to 45°, but leading step duration to all other amplitudes and trailing step duration to all amplitudes were similar to each other and increases in step duration during the moderate speed condition were consistent between all amplitudes.

As described in the section 7.3, it is clear that there is a link between stepping behaviour and eye movements during turning. Preventing eye movements via fixation during turns delays gait initiation and reduces the frequency of stepping. However, allowing free eye movements, but removing visual input, using either occlusion goggles or with eyes-closed, does not significantly alter turning behaviour from turns performed during full vision. Turning generally becomes slower when vision is unavailable, but gait initiation and stepping frequency are not significantly affected.

Vibration did not elicit many changes on stepping behaviour, but there was a significant interaction which showed that stepping frequency was significantly higher during the full vision condition with ipsilateral vibration than the no vision condition with ipsilateral vibration (Figure 5-6), which is interestingly the same effect that vibration had the on the peak fast phase velocity (Figure 5-4). If the vibration was in fact effective, this interaction may indicate that the same mechanism is either generating or at least modulating both nystagmus and stepping behaviour. Stepping behaviour and locomotion in general is thought to be mediated via central pattern generators in the spinal cord (Duysens and Van de Crommert, 1998). Central pattern generators are initially activated via supraspinal signals and generate rhythmic motor neuron activity which elicits alternating actions of extension and flexion in the limbs to generate locomotion. Physiological data from fictive locomotion in tadpoles suggests that signals arising from the spinal cord, presumably central pattern generators, generate nystagmus-like eye movements (Lambert *et al.*, 2012). During a variety of *in vitro* and *in vivo* preparation using *Xenopus* tadpoles, Lambert *et al.* found that stimulation of spinal central pattern generators which produced the undulatory tail movements which tadpoles use for swimming, also generated eye movements which were oppositely directed to horizontal head displacements, thus stabilising gaze. The authors concluded that the compensatory eye movements were generated by an efference copy of the central pattern generator signal for locomotion. There is the potential that the unidirectional effect of vibration on both stepping frequency and fast phase velocity was due to an efference copy of one signal which was sent to either one or both of the effectors causing similar behaviour, however this cannot be concluded.

7.5 Limitations

The head-mounted fixation device (Figure 4-1) used in Chapter 4 was designed to allow free head-on-trunk movement while preserving a fixed-distance fixation point thus preventing disconjugate eye movements. However, a caveat to this design was the fixation point was placed on a small board which occluded a portion of the central visual field. Additionally, to ensure stability of the device, a slow turn velocity was implemented in the speed control phase. A helmet-mounted device, rather than a head-mounted device, could have enhanced stability and allowed a faster, more natural turn speed as a control measure. Additionally, using a helmet the fixation point could have been attached directly overhead with limited obstruction of the central visual field. Future work which uses gaze fixation as a manipulation should incorporate these suggestions when designing a fixation device.

The sole use of EOG to measure eye movements did not provide information about the visual scene and the specific environmental features which the participant may have fixated on in order to stabilise their visual frame of reference. Therefore it remains unclear as to what visual factors might influence eye movement behaviour and this warrants further investigation. A gaze tracker could have been used in addition to EOG to determine fixation locations. However, concurrent use of EOG and gaze tracking along with either the occlusion goggles or a fixation device would not have been possible.

As stated in Chapter 5, a more concerted effort to control gaze direction during the standing and stepping-in-place protocols may have resulted in systematic results similar to those of Ivanenko *et al.* (1999) and Bove *et al.* (2002)

7.6 Future directions

Methodologically, a potential solution to the difficulties encountered during turning paradigms could be an immersive head mounted virtual reality system which includes eye tracking capabilities and is interfaced with motion tracking. A virtual reality environment could be programmed to make a standardised turn protocol which could be open-sourced, adapted for multiple systems and used across labs world-wide. A virtual reality environment would make visual manipulations simple as the environmental features could be programmed and could control for lab environments which may change over time. Additionally, for gaze fixation conditions, a fixed point could be programmed to appear at a certain distance and move with the visual field, which would eliminate the problems caused by a head mounted gaze fixation device. Additionally, visual manipulations which are not possible in a real lab environment, such as altering spatial characteristics of a room can be easily manipulated within a VR environment.

Another consideration for future turning research is making clear distinctions between turns which occur during ongoing locomotion and those that start from a static posture. Over the years in which the experiments described in this thesis were conducted, the body of turning literature has expanded, and the general findings suggest that both the biomechanics and sensory mechanisms differ between steering and standing turns, however, conclusions about behaviour during standing turns, such as the determination of an *en bloc* strategy, reference behaviour that is specific to turns during ongoing locomotion. Firstly, when beginning a turn from quiet stance, anticipatory postural adjustments are likely to be different from those which occur during ongoing walking. During locomotion, central pattern generators will already be activated and sending signals for alternating stepping motions, while turns from a static posture still require the initiation of gait. During the rotation, the velocity of the COM during steering decreases systematically with the increasing radius of the curve (Vieilledent *et al.*, 2001) while it appears that when the radius is constant, as in standing turns, segment velocity increases with increased turn amplitude. Finally, at the completion of a standing turn is usually a gait termination event, while during steering the completion of the turn could be a continuation of ongoing locomotion, the initiation of a different task, such as stair negotiation or steering in another direction or the ongoing locomotion could terminate. Additionally, available vision during steering and standing turns is vastly different as steering (usually) affords sight of the target or goal during the entire course of locomotion while standing turns outside of the visual field are more dependent on online control. The relative contributions of vestibular signals from the SCCs and the otoliths are likely to be quite different as the translation component during locomotion is much higher than during standing turns. As investigations into turns continue to happen, it is likely that clear differences between these two types of turns will emerge.

7.7 Clinical Implications

The ultimate aim of performing research on turning is to be able to determine how turning is normally controlled, what is going wrong when people fail to turn successfully, and what can be done to correct these deficits. We have shown that eye movements are a necessary part of performing a turn, specifically in initiating gait in a timely manner and that intersegmental coordination is reliant upon regular nystagmus.

As there are many clinical populations have both turning difficulties and eye movement deficits, this lends further support to the notion that altered eye movements may lead to turning impairments. While many studies have focused on turning behaviour in clinical populations, those that look at oculomotor behaviour usually only isolate the first fast phase for examination and do not analyse nystagmus throughout the course of the turn. The results of Chapter 4 suggest that not only the initial, but all eye movements are necessary for normal turning coordination. It may be particularly interesting to examine eye movement behaviour in PD patients to see if fixation induces freezing events and if spontaneous freezing is related to a change in eye movement behaviour. While many more studies need to be performed to isolate which eye movement problems may lead to turning difficulties or falling, it is likely that by understanding these problems a new visual or eye movement strategy can be developed to enable successful turn negotiation. Such strategies have been implemented in precision stepping in older adults who were deemed to be at increased risk for falling (Young and Hollands, 2010) and in cerebellar ataxia patients (Crowdy *et al*. 2002). These experiments have shown that simply explaining appropriate visual strategies or rehearsing eye movements prior to stepping increases the accuracy of subsequent stepping performance. Such a strategy could be used during turning to implement strategic saccadic movements to utilise a gaze anchoring mechanism and potentially enhance turning ability.

7.8 Summary and conclusions

The work described in this thesis has provided evidence that both intersegmental coordination and nystagmus characteristics are systematically altered by changes in turn speed and turn amplitude. We have clearly demonstrated that the timing of eye, head and axial segment reorientation onset does not accurately represent coordination during the turn. We have provided further evidence that anticipatory eye movements are not visually driven and that suppressing anticipatory eye movements causes delayed gait initiation and decreases stepping frequency throughout the turn. We found that stimulating neck proprioceptors with vibration to evoke the perception of head rotation causes early turn initiation and appears to upregulate fast phase velocity characteristics. Lastly, we found divided attention caused by dual-tasking delays turn onset, but eye and body coordination are unaffected. We conclude that oculomotor nystagmus during turning represents a crucial component of an automatic, subcortically generated motor synergy, the release of which is dependent on cortical and sensory input (i.e. vision and neck proprioception). We propose that standing turns are organized centrally as part of a whole-body gaze shift rather than a specialized adaptation to conventional locomotion.

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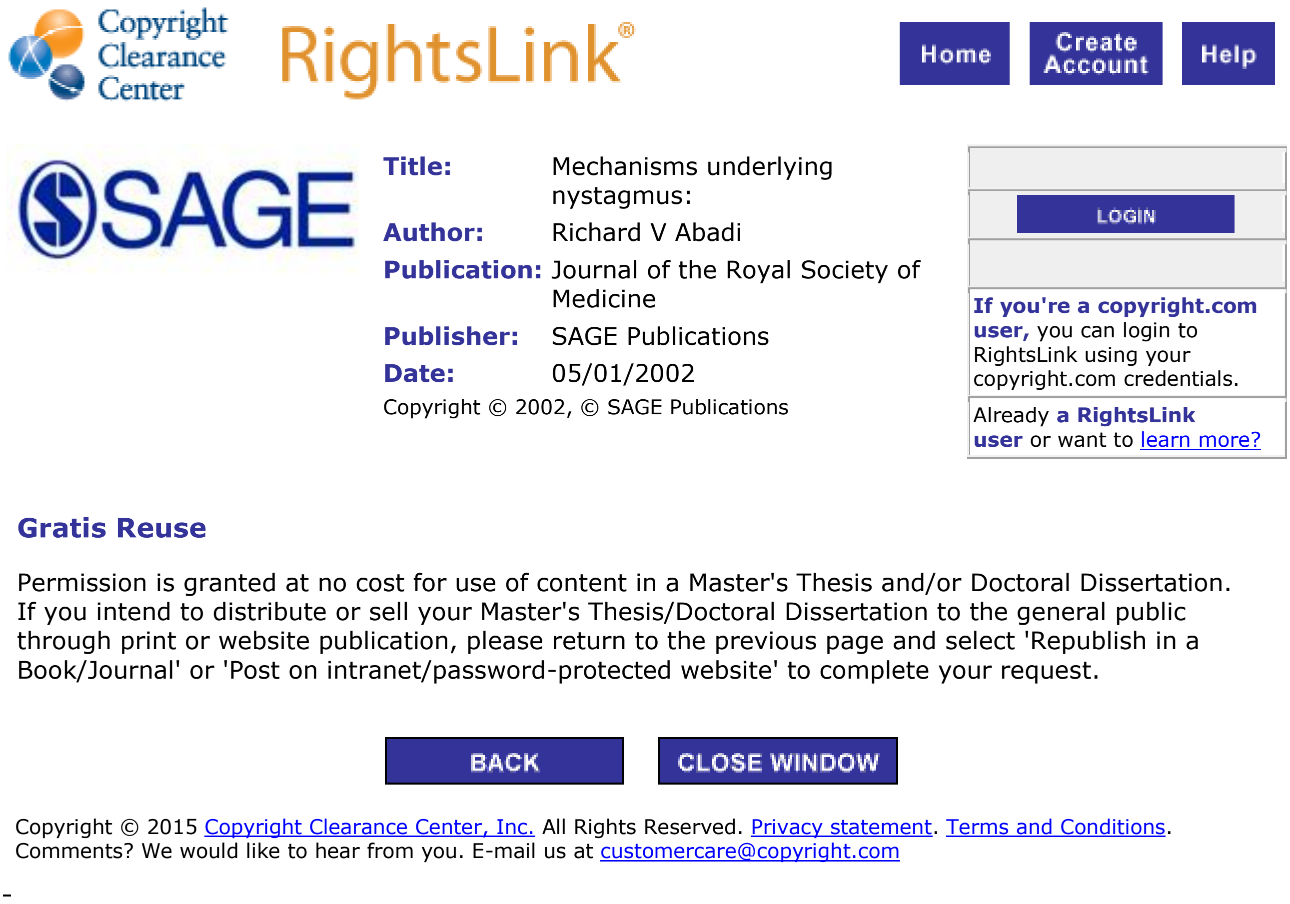

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