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RESEARCH ARTICLE

Keep looking ahead? Re-direction of visual fixation does not always occur during an unpredictable obstacle avoidance task

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Abstract Visual information about the environment, especially fixation of key objects such as obstacles, is critical for safe locomotion. However, in unpredictable situations where an obstacle suddenly appears it is not known whether central vision of the obstacle and/or landing area is required or if peripheral vision is sufficient. We examined whether there is a re-direction of visual fixation from an object fixated ahead to a suddenly appearing obstacle during treadmill walking. Furthermore, we investigated the temporal relationship between the onset of muscle activity to avoid the obstacle and saccadic eye and head movements to shift fixation. Eight females (mean ± SD; age = 24.8 ± 2.3 years) participated in this experiment. There were two visual conditions: a central vision condition where participants fixated on two obstacles attached to a bridge on the treadmill and a peripheral vision condition where participants fixated an object two steps ahead. There were two obstacle release conditions: only an obstacle in front of the left foot was released or an obstacle in front of either foot could be released. Only trials when the obstacle was released in front of the left foot were analyzed such that the difference in the two obstacle conditions was whether there was a choice of which foot to step over the obstacle. Obstacles were released randomly in one of three phases during the step cycle corresponding to available response times between 219 and 462 ms. We monitored eye and head movements along with muscle activity and spatial foot parameters. Performance on the task was not different between vision conditions. The results indicated that saccades are rarely made ($< 18\%$ of trials) and, when present, are initiated ~ 350 ms after muscle activity for limb elevation, often accompanied by a downward head movement, and always directed to the landing area. Therefore, peripheral vision of a suddenly appearing obstacle in the travel path is sufficient for successful obstacle avoidance during locomotion: visual fixation is generally not re-directed to either the obstacle or landing area.

Keywords Saccade · Obstacle avoidance · Locomotion · Vision · Reaction time · Human

Introduction

Environmental hazards that may cause a trip, such as a hole in the pavement or a curb, make it necessary to rely heavily on visual information during locomotion. Visual fixation is important to extract relevant environmental information for adaptive locomotion (Patla 2004) as the image of the object or characteristic of

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interest is projected onto the region of the retina with the highest visual acuity, the fovea. If central vision is required to detect, monitor, and obtain spatial details of an approaching obstacle or other hazard, saccadic eye movements elicited by the oculomotor system in conjunction with head movement to shift the image onto the fovea may be necessary for visuo-motor processing to evoke and coordinate a lower limb movement. Reorientation of gaze may also be more important for the landing phase after obstacle or hazard avoidance to ensure safe foot placement. Alternatively, attention may be shifted covertly, in the absence of eye or head movements (Findlay and Gilchrist 2003; Posner 1980), and thus peripheral visual information from the lower visual field of the obstacle or hazard may be ample to guide lower limb movement safely.

Visual fixation allows the central nervous system (CNS) to mark specific spatial points (or anchors) to help guide limb movement. Di Fabio et al. (2003b) argue stepping movements use this visual anchoring behavior, proposed by Johansson et al. (2001) for object manipulation, and hence saccadic eye movements are linked to stepping. Studies on obstacle avoidance suggest that visual input is utilized during the approach phase, which is evident from visual fixations directed to the obstacle (Patla and Vickers 1997) or downward saccades made to an area behind the obstacle following a cue as to which limb to initiate the step over the obstacle (Di Fabio et al. 2003a). However, peripheral vision is sufficient while stepping over the obstacle as fixation is directed to the landing area (Patla and Vickers 1997) or upward saccades are made to adjust gaze to a forward looking direction (Di Fabio et al. 2003a) and not the obstacle during the cross-over phase. Patla and Vickers (2003) have also shown that individuals fixate two steps ahead when walking on specific targets in the travel path, whereas Hollands et al. (1995) showed that just prior to every step onto a target horizontal saccadic eye movements directed to the stepping area occurred. It is possible that differences in the experimental set-up may account for these discrepancies. Nevertheless, in stable environments visual fixation on potential hazards and safe landing areas about two steps ahead may be adequate for safe travel.

In more unpredictable environments where one often has to respond to unexpected changes and the available response time to avoid contact is short, such as the sudden appearance of an obstacle in the travel path, fixation behavior is not known. Behaviorally, obstacle avoidance reactions to a suddenly appearing obstacle during locomotion on a treadmill elicit rapid responses of approximately 120 ms as reflected in changes in foot acceleration profiles (Weerdesteyn et al. 2004). In addition, recent experiments on a stepping task where the step target is displaced on toe-off suggest that the nervous system can rapidly alter lower limb trajectory in response to a visual stimulus without sacrificing balance (Reynolds and Day 2005a) and on-line monitoring of the limb is important for accurate foot placement (Reynolds and Day 2005b).

Clearly, fast visuo-motor processing may allow an individual to accommodate unpredictable ground conditions during locomotion and stepping movements. The question arises as to whether there is a re-direction of visual fixation to the sudden change in the environment (i.e. the appearance of an obstacle in the travel path) during walking. The visual system is certainly designed to detect novel stimuli in the visual field as evident from orienting reactions to new stimuli, which may include suddenly appearing obstacles. Although mechanisms exist to suppress these reactions, for example when one attentively focuses on a given stimulus, whether this type of suppression also occurs when one fixates a target while trying to avoid a potentially destabilizing obstacle is not known.

In this study, we examined whether central vision is required to detect and successfully avoid a suddenly appearing obstacle during locomotion on a treadmill. In particular, we addressed whether vertical saccades were made to an obstacle when visual fixation of a target made the image of an obstacle present in the peripheral visual field. Thus, if an individual's attention is directed to a target ahead (such as when scanning the environment in front) and an obstacle suddenly appears in the periphery, is a saccadic eye and/or head movement necessary to shift central vision to this new challenge? And, if so, does such an orienting response have to precede the lower limb motor response (so that visual information is sampled first before one makes motor decisions necessary for obstacle avoidance)? Thus, we also explored the temporal organization of vertical saccades, head movement, and the onset of muscle activity geared towards altering the lower limb to avoid the approaching obstacle.

Methods

Participants

A total of eight female participants (mean ± SD; age = 24.8 ± 2.3 years; height = 1.75 ± 0.07 m; mass = 67.4 ± 11.1 kg) were studied. Participants did not have any neurological, muscular, or joint disorder that could affect their performance and/or behavior in this study. Participants wore their own corrective lenses if necessary. The Ethical Board of the region Arnhem–Nijmegen approved the protocol and participants gave informed consent to participate.

Procedure

The participants walked on a treadmill (ENRAF Nonius, Type EN-tred Reha) at a fixed speed of 3 km/h and at a fixed position so that the most anterior position of the toes was approximately 10 cm in front of the obstacles prior to their release. A bridge, to which an electromagnet was attached, was placed over the front of the treadmill (see Weerdesteyn et al. 2003, 2004, 2005) and held two brown-colored wooden obstacles via a piece of iron embedded in each (see Fig. 1a). The length, width, and height of each obstacle were 40, 30, and 1.5 cm, respectively. The obstacles could be released independently by a trigger from a computer and fell in front of either the left or right foot depending on the condition. Note, only one obstacle was released at a time. Participants had to step over the obstacle: stepping aside from the obstacle with the ipsilateral foot was not allowed during the task. Depending on when the obstacle was released (see below) a minimum step shortening or lengthening of 30–60% was necessary to avoid the obstacle. Participants wore ear plugs that blocked any auditory cue (i.e. the sound of the obstacle falling onto the treadmill belt) during the experiment.

There were two conditions with respect to vision, namely one with central and one with peripheral vision. Central vision referred to the task of focusing on the obstacles secured to the electromagnetic bridge on the treadmill prior to obstacle release (see Fig. 1). In contrast, peripheral vision referred to the task of focusing on a red cylindrical object placed on the floor in front of the treadmill approximately two steps ahead of the participant prior to obstacle release (this corresponds to peripheral vision of a target at ~27° eccentricity). Previous research has indicated that individuals fixate approximately two steps ahead during a target stepping task (Patla and Vickers 2003). Participants were instructed to remain fixated on this object until they detected obstacle release and then were free to look where they thought necessary. Furthermore, there were two conditions with respect to the obstacle used. In the left-obstacle conditions (L-obstacle) only the obstacle in front of the left foot could be released. In the left or right-obstacle conditions (L/R-obstacle) either the obstacle in front of the left or right foot could be released with equal probability.

A total of 120 trials were performed in which participants had to avoid the obstacle dropped onto the moving treadmill belt. The first 30 trials were considered practice to allow participants to become familiar with treadmill walking and stepping over the obstacle. Participants were free to look anywhere they wanted in these trials. Blocks of trials were performed for each of four experimental conditions: (1) L-obstacle, central vision, (2) L-obstacle, peripheral vision, (3) L/R-obstacle, central vision, and (4) L/R-obstacle, peripheral vision. Each block was presented in random order to each participant. The obstacle was only released once a stable walking pattern was accomplished such that there were five strides with a maximum difference of 50 ms between consecutive strides. To ensure that the participants followed the instructions the point of fixation from an eye tracker system was monitored on-line (see below). Participants were informed of the condition before each block.

The obstacle was released in one of three phases of the step cycle (Early, Mid, or Late) corresponding to available response times (ARTs) of 462.1 ± 45.3, 317.1 ± 38.9, and 219.0 ± 37.1 ms, respectively. ART is defined as the time between obstacle release and the moment that the hallux marker would cross the front of the obstacle when no avoidance reaction would occur, such that obstacle avoidance trials with smaller ARTs were more challenging (Chen et al. 1994a). The Early phase corresponded to obstacle release in mid to late stance of the crossing limb. The Mid phase corresponded to obstacle release in late stance to early swing of the crossing limb. And the Late phase corresponded to obstacle release in early to mid swing of the crossing limb. A total of five trials of each phase (Early, Mid, and Late) were performed for each obstacle such that there were 15 trials in the L-obstacle condition blocks and 30 trials in the L/R-obstacle condition blocks. Each trial within the blocks was also randomized. Only trials were the obstacle in front of the left foot was released were used for further analysis.

In addition, due to the constraints of the task a control experiment was performed to test the importance of vision for avoiding the obstacle and to see whether auditory feedback was sufficient to elicit the obstacle avoidance reactions. Four participants each performed 30 trials with an identical procedure to that of the peripheral vision condition except that their lower visual field was blocked (with the use of glasses) so that they could not see the obstacle and had to rely on an auditory cue (obstacle falling onto the treadmill belt) to evoke a response.

Measurement systems

Reflective markers were attached to each obstacle and bilaterally to the heel and hallux of the participants. A

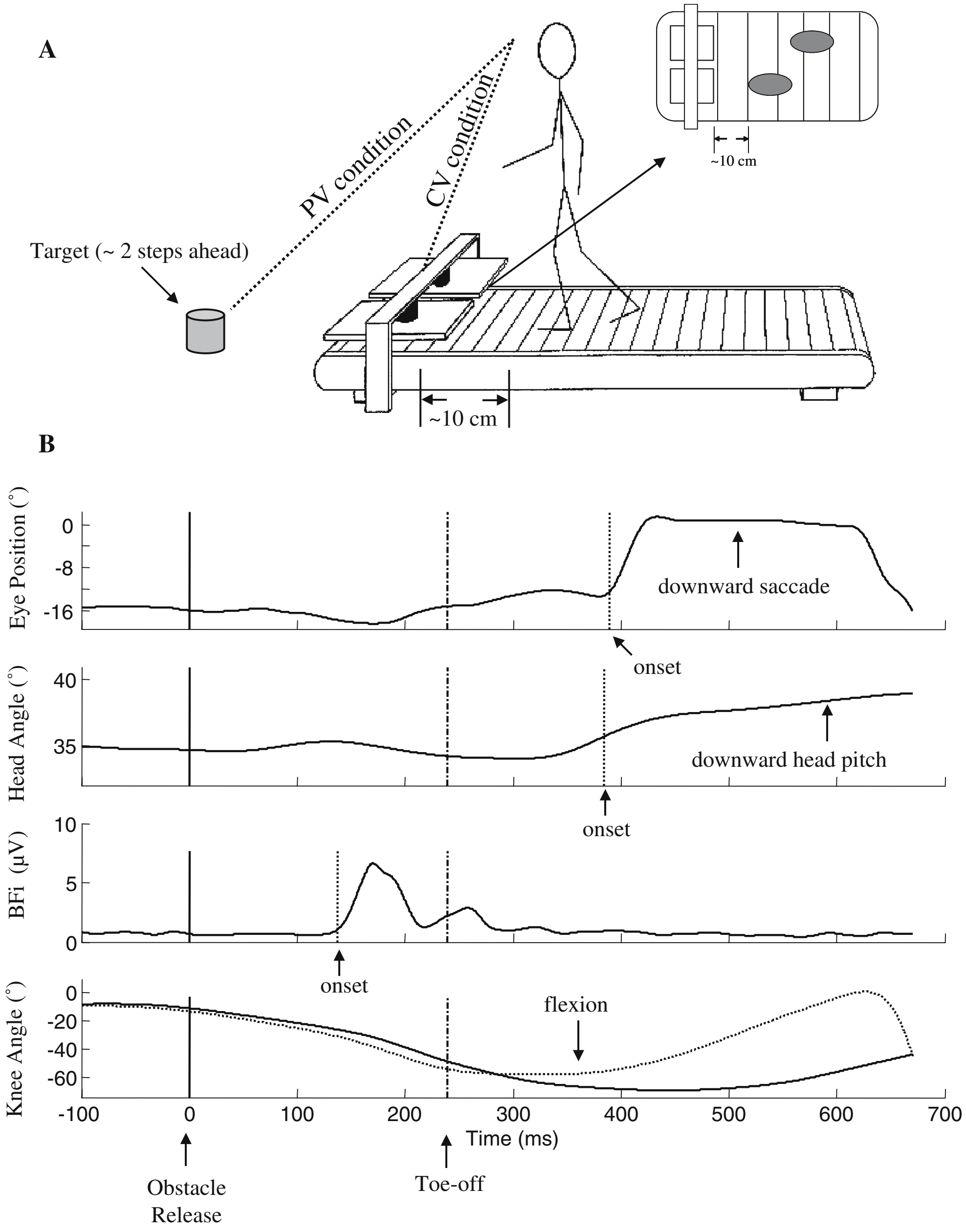

Fig. 1 **a** Experimental set-up. *PV* peripheral vision, *CV* central vision. **b** Typical profiles of one participant (one representative trial) of a downward saccade, downward head pitch, and muscle activity from the ipsilateral biceps femoris muscle (*BFi*). Ipsilateral knee joint angle shows knee flexion over the obstacle comparing the mean control strides (*dashed line*) with an obstacle avoidance stride (*solid line*)

six-camera 3D motion analysis system (Primas®) recorded marker positions at a sample rate of 100 Hz. Determination of heel strikes and obstacle release has been described previously (Weerdesteyn et al. 2004, 2005). Bilateral ankle, knee, and hip joint angles were recorded via six electro-goniometers (Penny and Giles, Type M180) and sampled at 2,400 Hz. Surface electromyography (EMG) was collected from bilateral tibialis anterior, medial head of gastrocnemius, rectus femoris, and biceps femoris using self-adhesive electrodes (Ag/AgCl) (MediTrace ECG 1801 Pellet) placed ~ 2 cm apart and longitudinally on the belly of the muscle. The EMG signals were band-pass filtered (10–500 Hz) and sampled at 2,400 Hz.

A lightweight (227 g), video-based eye tracker (Polhemus VisionTrak ETL-500) with 0.5° precision was worn on the head and used to record movements of both eyes. With this system infra-red corneal and pupil reflections are used to determine visual fixation, relative to the head, and this information is displayed as cross-hairs that are superimposed on the video images recorded by a ‘scene camera’ rigidly mounted on the head. This ‘scene camera’ records the field of view resulting from changes in head position and orientation. The eye tracker was calibrated for each participant using a five-point calibration procedure which required the person to fixate a series of five points in a grid on the floor in front of them and was re-checked periodically throughout the testing procedure. Position of the fixation, referred to as the point of fixation, was monitored on-line by the experimenters to ensure the participants were focusing on the correct target (i.e. obstacles or cylindrical object two steps ahead depending on whether it was the central or peripheral vision condition, respectively). The image was also recorded to a VHS tape to ensure the accuracy of the on-line monitoring and to determine where the participant directed fixation if a saccade was made during the task. The vertical amplitude of the eye movements were recorded at 120 Hz.

Fastened to the eye tracker system was a Polhemus FasTrak that recorded head angles relative to the trunk in the saggital plane (i.e. forward head pitch) and was sampled at 120 Hz. The analog eye-angle and head pitch angle output channels were connected to an AD board, which enabled data to be sampled synchronously with the EMG data, and were re-sampled at 2,400 Hz.

Data analysis

Data analysis was performed using custom written software in MATLAB (The Mathworks, version 6.5). Only trials where the obstacle in front of the left foot was released were analyzed. The presence of saccades during the task was investigated for the peripheral vision conditions to determine whether the participants required shifting the image of the obstacle onto the fovea. Blink artifacts in the oculomotor data were interpolated with a cubic spline function and low-pass filtered at 30 Hz (zero-lag, Butterworth filter). The mean and standard deviation of the signal from each eye prior to obstacle release was determined. The onset of a downward saccade was defined as the time between obstacle release and when the recorded eye movement of both eyes exceeded two standard deviations of the mean signal and remained above this value for at least 30 ms as determined by a computer algorithm and confirmed by visual inspection.

Head angle (i.e. head pitch) data were low-pass filtered at 10 Hz (zero-lag, Butterworth filter) prior to analysis. Zero head pitch (in the saggital plane) was defined as when the head was positioned upright and parallel to the body and perpendicular to the ground (i.e. zero degrees at horizontal plane). Hence, larger head pitch angles represented greater head movement downward as occurred when gaze was directed at the ground. The mean and standard deviation of the head pitch signal prior to obstacle release was determined. The onset of a downward head pitch was defined as the time between obstacle release and when the head pitch angle exceeded two standard deviations of the mean signal and remained above this value for at least 30 ms as determined by a computer algorithm and confirmed by visual inspection. The maximum head pitch after an onset in deviation from the normal position was also determined.

The ipsilateral biceps femoris (BFi) was consistently activated first for the avoidance response following obstacle release. Consequently, only the latency of this muscle was investigated in this study. EMG activity of the BFi was full-wave rectified and low-pass filtered at 25 Hz (zero-lag, Butterworth filter). Strides prior to obstacle release in 30 trials were used as control strides. Control stride muscle activity was ensemble averaged and two standard deviations around the mean were calculated. Data was aligned to heel contact. Subsequently, the muscle onset latency was determined by a combination of computer algorithm and visual inspection (to ensure data quality) on a single trial basis. Onset latency of the BFi was defined as the time between obstacle release and the moment that the EMG activity exceeded two standard deviations of the control stride activity for at least 30 ms.

Spatial parameters of successful avoidance responses were also determined. To avoid the obstacle during walking two distinct strategies can be utilized: the long step strategy (LSS) and short step strategy (SSS). In an LSS the obstacle is crossed by means of a lengthened crossing step while in an SSS the pre-crossing step is shortened and the obstacle is crossed in the next step (Chen et al. 1994b; Weerdesteyn et al. 2003, 2004, 2005). For SSS avoidance reactions, toe distance (horizontal distance from hallux marker to the edge of the obstacle in the step prior to crossing the obstacle), foot clearance (vertical distance between the foot and obstacle), and heel distance (horizontal distance between the heel marker and the edge of the obstacle in the step over the obstacle) were calculated. For the LSS avoidance reactions only foot clearance and heel distance were determined as there is no pre-crossing step in which to calculate toe distance. An unsuccessful trial was defined as foot contact with the obstacle and was recorded for further analysis.

Statistical analysis

Our primary means of determining whether central vision of the suddenly approaching obstacle was needed for the task was to assess the presence of saccadic eye movements that re-directed fixations to the obstacle from the target two steps ahead in the peripheral vision condition. Since central vision can also be re-directed through a combination of head and eye movements or head movements alone, we examined changes in head pitch downward between the conditions. A one-way repeated measure ANOVA compared differences in head pitch angle where the dependent variables were (1) mean head pitch angle prior to obstacle release in the central vision condition, (2) mean head pitch angle prior to obstacle release in the peripheral vision condition, (3) maximum head pitch angle after onset of a deviation from the control trials after obstacle release accompanying a downward saccade, and (4) maximum head pitch angle after onset of a deviation from the control trials after obstacle release with no saccade present.

To further determine whether central vision was needed for the task, performance measures including the number of unsuccessful trials, BFi onset latency, and spatial parameters (toe distance, foot clearance, and heel distance) were investigated. A three-way (obstacle, vision, and phase) repeated measures analysis of variance (ANOVA) compared BFi latency among participants. Note that the obstacle factor has two levels and refers to the fact that participants were aware an obstacle would only be released in front of the left foot or that an obstacle could be released in front of either foot. Only trials were the obstacle was released in front of the left foot were analyzed. As spatial parameters of the avoidance response are known to depend on the avoidance strategy and the phase of obstacle release (Weerdesteyn et al. 2003), separate two-way (obstacle and vision) repeated measures ANOVAs with phase as the covariate were performed for an SSS (dependent variables: toe distance, foot clearance, heel distance) and an LSS (dependent variables: foot clearance, heel distance) avoidance reaction.

Our second question centered on determining the difference in temporal sequencing between the onset of an avoidance response (i.e. onset of the ipsilateral biceps femoris muscle), saccade latency, and onset of head pitch angle deviation from control trials, if a saccadic eye movement was made in the peripheral vision condition. A one-way (response type: muscle onset, saccade onset, and head movement onset) ANOVA was performed. Only trials in which all three dependent variables were present (BFi was activated, a saccade was present, and a head pitch deviation occurred) were included in this particular analysis.

All statistical analyses were performed using SPSS for Windows, version 12, with an alpha level of 0.05.

Results

All participants were able to perform the obstacle avoidance task without falling despite short available response times. As evident from our additional experiment, visual information is highly important for successful performance of the task. The mean failure rate when the lower visual field was blocked (and only an auditory cue was available) was 26.8 ± 16.6 versus 2.9 ± 2.8% in the peripheral vision condition and 2.1 ± 3.1% in the central vision condition.

Figure 1b illustrates a typical trial from one participant where a downward saccade and head pitch were made following the onset of the ipsilateral biceps femoris muscle. Knee joint angle of the lower limb avoiding the obstacle (solid line) deviated from control strides (dotted line) just before 300 ms following obstacle release and demonstrated greater knee flexion following this deviation.

Eye and head movements in response to a suddenly appearing obstacle in the travel path

In the central vision conditions, gaze was directed to the left obstacle in the L-obstacle condition and to the middle of the two obstacles in the L/R-obstacle condition prior to their release. Interestingly, in the central vision conditions where participants directed gaze to the obstacles we regularly observed an ocular following response in that the eyes tracked the approaching obstacle after it was suddenly released.

In the peripheral vision condition, where participants directed gaze to a target approximately two steps ahead prior to obstacle release, downward saccades were only made in 18% of trials (see Table 1). All participants made at least two saccades. When a saccade was made, albeit infrequent, the point of fixation was directed to the landing area behind the obstacle in all cases. The mean eye rotation caused by the saccade was 20.5 ± 8.4°. In approximately 83% of trials in which a saccade occurred, the eye movement was accompanied with a downward head pitch (Table 1) of 5.1 ± 2.9°. It would require an approximate 27° change in eye/head position to bring the fovea from the target to the obstacle/step landing area. The saccadic eye movement and downward head pitch combined

Table 1 Saccade frequency count in peripheral vision condition

	Trials #	Saccade # (%)	Head pitch with saccade # (%)	Head pitch alone # (%)
Early phase	72	10 (13.7%)	8 (11.0%)	43 (58.9%)
Mid phase	76	17 (22.4%)	16 (21.1%)	30 (39.5%)
Late phase	75	13 (17.3%)	9 (12.0%)	30 (40.0%)
Total	223	40 (17.9%)	33 (14.8%)[a]	103 (46.2%)
L-obstacle	117	19 (16.2%)	16 (13.7%)	57 (48.7%)
L/R-obstacle	106	21 (19.8%)	17 (16.0%)	44 (41.5%)

[a] 82.5% of saccades had an accompanying head pitch

resulted in a change of approximately this value (25.6°).

There was a large range of saccade onset latencies (93–1,016 ms) among participants. The mean onset latencies for the L-obstacle condition for the Early, Mid, and Late phases were 389.0 ± 134.8, 701.5 ± 236.1, and 475.7 ± 346.0 ms, respectively. The mean onset latencies for the L/R-obstacle condition for the Early, Mid, and Late phases were 433.1 ± 178.5, 364.0 ± 206.1, and 483.2 ± 227.0 ms, respectively.

The onset of a deviation in downward head pitch also showed a range of values (185–1,056 ms). The mean onset latencies for the L-obstacle condition for the Early, Mid, and Late phases were 400.6 ± 75.4, 550.1 ± 286.0, and 524.4 ± 276.4 ms, respectively. The mean onset latencies for the L/R-obstacle condition for the Early, Mid, and Late phases were 497.1 ± 63.1, 404.7 ± 161.3, and 479.3 ± 136.0 ms, respectively.

Figure 2a, based on trials in which the obstacle in front of the left foot was released, shows head pitch angle in the central and peripheral vision conditions prior to obstacle release and in the peripheral vision condition after obstacle release. There was a significant difference between the vision conditions ($F_{3,5} = 23.03$, $P = 0.002$). There was a clear difference in angle (approximately 10°) between the mean head pitch angle prior to obstacle release in the central and peripheral vision conditions. The figure also illustrates the maximum head pitch angle obtained after a deviation from the control trials trajectory for the peripheral vision conditions both when a saccade was present and when head pitch occurred alone. The maximum angle in these latter peripheral vision trials was somewhere between the mean angles in the two visual conditions. The magnitude of the downward head pitch angle for the trials where a saccade was and was not present was 5.1 ± 2.9° and 3.9 ± 1.9°, respectively. Although in almost 50% of obstacle avoidance trials a downward head pitch was made without a saccade, importantly, the point of fixation remained on the target two steps ahead of the person and was never re-directed to the landing area at any time during the trial. The downward head pitch in these instances was accompanied by an upward eye movement (see Fig. 2b). Thus, although a slight downward head pitch was made central vision of the obstacle and the landing area was not available. There were no differences in maximum head pitch angle between obstacle conditions and obstacle release phase ($P < 0.05$).

Obstacle avoidance performance measures

There were few unsuccessful obstacle avoidance trials. In fact, there were only 13 unsuccessful trials (i.e. foot contact with obstacle) in the experimental conditions: 6 in the central vision conditions and 7 in the peripheral vision conditions. There were five unsuccessful trials during the initial practice condition. In all seven of the unsuccessful trials in the peripheral vision condition no saccades were made.

There were no significant differences (for obstacle or vision condition) in foot clearance over the obstacle for both the SSS and LSS avoidance reactions ($P < 0.05$). In addition, there were no differences in toe distance for the SSS avoidance reactions ($P < 0.05$). In contrast, heel distance differed depending on the vision condition for both the SSS and LSS avoidance reactions. Specifically, in an SSS avoidance reaction heel distance after crossing the obstacle was larger in the central vision condition (main effect: $F_{1,13} = 6.26$, $P = 0.026$; central vision = 297 ± 113 mm; peripheral vision = 278 ± 96 mm). On the other hand, in the LSS avoidance reaction heel distance was larger in the peripheral vision condition (main effect: $F_{1,6} = 11.17$, $P = 0.016$; central vision = 100 ± 45 mm; peripheral vision = 123 ± 46 mm).

The ipsilateral biceps femoris muscle was consistently the first muscle to respond to the sudden appearance of the obstacle and initiate a step strategy to avoid contact. The mean onset latency of this muscle among the participants ranged from 108 to 149 ms. The three-way ANOVA demonstrated a significant

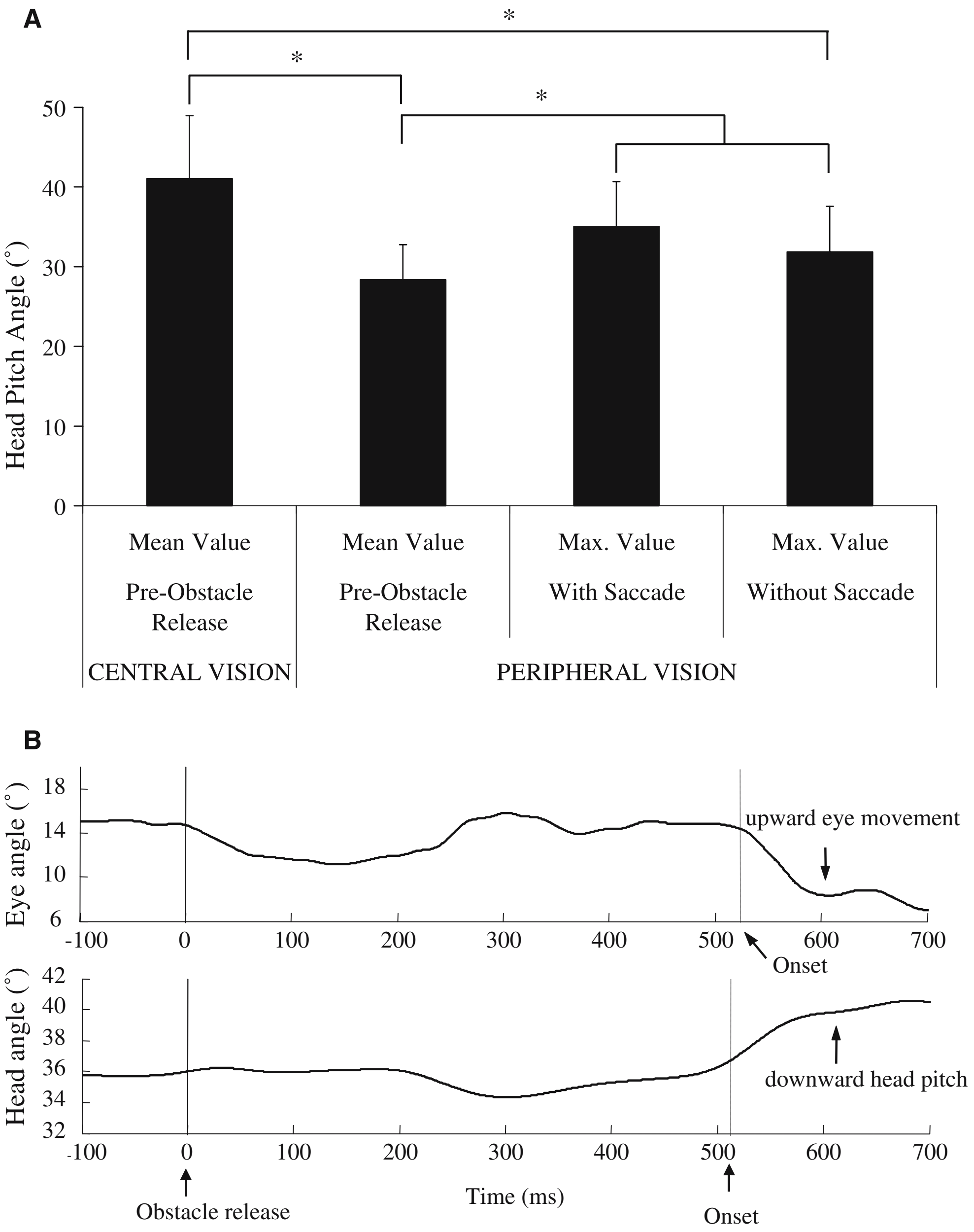

Fig. 2 Head movements during obstacle avoidance on a treadmill. **a** Illustrates head pitch angles where larger head pitch angle represents greater downward head movement. Mean values refer to the mean head pitch angle calculated prior to obstacle release whereas the maximum values refer to the maximum head pitch angle calculated following obstacle release. **b** Typical profiles of one participant (one representative trial) of the upward eye movement accompanying the downward head pitch trials when no downward saccade was made in order to keep the point of fixation on the target

obstacle ($F_{1,6} = 9.95$, $P = 0.020$) and phase ($F_{2,5} = 6.73$, $P = 0.038$) main effect. Onset latency of the ipsilateral biceps femoris muscle did not differ between visual conditions ($F_{1,6} = 0.005$, $P = 0.944$; mean ± SD; central vision = 128.9 ± 20.4 ms; peripheral vision = 129.1 ± 21.1 ms). In addition, the ipsilateral biceps femoris onset latency was significantly earlier in the L-obstacle condition (mean ± SD; 123.2 ± 20.5 ms) compared to the L/R-obstacle condition (mean ± SD; 134.8 ± 19.3 ms). Furthermore, onset latency occurred sooner when the obstacle was released in the late phase (Late phase = 120.0 ± 17.9 ms) corresponding to an available response time of approximately 219 ms compared to when the obstacle was released with longer ART (mean ± SD; Early phase = 133.7 ± 23 ms; Mid phase = 133.3 ± 18.3 ms). There were no significant two- or three-way interactions ($P < 0.05$).

Temporal relationship between muscle onset latency, saccade onset, and head pitch deviation

One alternative question was whether saccades, when present, have to precede the lower limb motor response (see Introduction). The ipsilateral biceps femoris muscle was clearly activated prior to the onset of a downward saccade, when present, and downward head pitch (see Figs. 1, 3). In fact, the biceps femoris was activated on average 350 ms before the presence of a saccadic eye movement or downward head pitch. The differences in onset latencies between the biceps femoris muscle and the saccades and head pitch were highly significant ($F_{2,63} = 27.4$, $P = 0.0001$).

Discussion

The visual system is uniquely designed to provide the CNS information regarding upcoming environmental conditions for planning safe forward progression. Studies on obstacle avoidance and precision stepping suggest that saccadic eye movements are linked to step initiation (Di Fabio et al. 2003a, b; Hollands et al. 1995; Hollands and Marple-Horvat 2001). In contrast, Patla and Vickers (1997) do not show this link. The results of this study suggest that peripheral vision of a suddenly approaching obstacle is sufficient for triggering an appropriate obstacle avoidance reaction and for safe foot placement over the obstacle as saccades were infrequent during the peripheral vision conditions. Specifically, we found saccades were made in less than 18% of trials. Even when the task was made more challenging in that either obstacle could be released (i.e. L/R-obstacle condition) the frequency of saccades were unaffected. Zettel et al. (2005) have recently shown visual fixation is re-directed to the landing area in less than 40% of trials during standing platform translations, which required a compensatory step over an obstacle and/or to a target on the floor. Importantly, performance (i.e. step parameters and ipsilateral biceps femoris onset latency) on our task was not affected by the vision conditions.

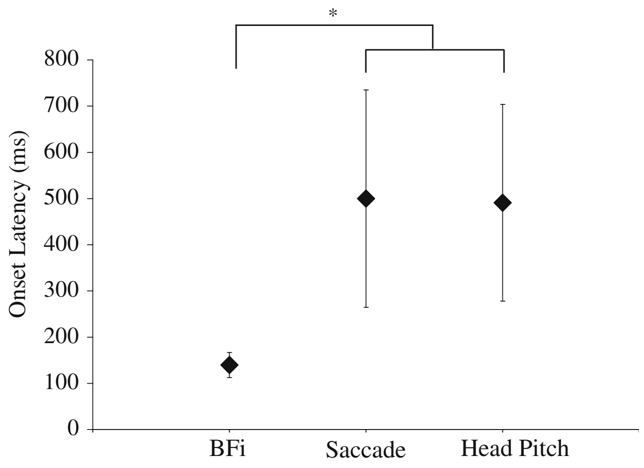

Fig. 3 Temporal organization of the vertical saccades, head movement, and the onset of muscle activity geared towards altering the lower limb to avoid the approaching obstacle

The ability of the nervous system to utilize information from peripheral vision from the lower visual field is vital for safe travel in an unpredictable environment. The visual scene is far too large and complicated for the nervous system to re-direct visual fixation so that the fovea ‘sees’ all areas of interest in sufficient time for processing details and guiding locomotion. Rather, attention can be directed covertly (i.e. in the absence of eye movements) to salient areas (Findlay and Gilchrist 2003; Posner 1980). While fixation is not re-directed in our study, it is likely attention has been shifted to the obstacle in the peripheral vision conditions. The premotor theory of attention proposed by Rizzolatti and colleagues (Rizzolatti et al. 1987; Sheliga et al. 1994, 1995) argues that covert and overt attention share common neural mechanisms and that shifts in attention are accomplished by planning eye movements. Thus, the oculomotor system may program a saccadic eye movement in the peripheral vision condition but the visual system determines that re-fixation is not necessary and as a result the saccade is aborted.

Peripheral vision from the lower visual field may be particularly important for detecting potential hazards that we do not see in advance such as when an animal runs directly in front of us while we fixate on a location ahead, when we need to read a sign in front of us, or while we converse with someone walking beside us. In fact, visually guided pointing actions are performed better when viewed with the lower visual field compared to the upper visual field (Brown et al. 2005; Danckert and Goodale 2001; Khan and Lawrence 2005). In humans, the density of ganglion cells in the superior hemiretina is 60% greater than the inferior hemiretina suggesting a processing bias for visual stimuli in the lower visual field (Curcio and Allen 1990). Furthermore, Portin et al. (1999) using magnetoencephalography have reported stronger cortical activations in the calcarine fissure of the occipital cortex from visual stimuli in the lower visual field. Thus, we are particularly suited to utilize visual information obtained from the periphery in the lower visual field.

The lack of saccadic eye movement expression may be due to the fact that visual fixation of the path ahead is necessary for safe locomotion. This would enable the nervous system to predict the trajectory adjustments required by the terrain. Alternatively, it is possible that the lack of saccades were due to the constrained path of treadmill walking and/or predictable obstacle dimensions and landing area characteristics. Indeed, treadmill walking may create a cognitive set that removes the intention of exploration and thus negates the saccade-step linkage. However, incorrect foot placement past the obstacle may be detrimental in that the treadmill belt is continuously moving (and thus the person cannot simply abort their chosen movement and stop if their step was misguided) and/or the treadmill belt's dimensions restrict foot placement to occur on the belt or the person would fall off the treadmill. Hence, treadmill walking does not necessarily equate to over-ground walking in all aspects. Despite the predictable obstacle dimensions and landing area characteristics the obstacle avoidance task was challenging. The obstacle was released randomly in different phases of the step cycle such that the ART was between 219 and 462 ms and we manipulated whether the obstacle was released in front of the left or right lower limb. Furthermore, our additional experiment suggests that some form of visual information regarding obstacle position is important for successful obstacle avoidance. When participants had their lower visual field blocked and had to rely on an auditory cue to evoke a response, the mean failure rate was ~27% (compared to ~3% in the peripheral vision condition).

Apart from the use of the treadmill and predictable obstacle dimensions, there are a few other limitations that should be addressed. First, the sample size was relatively small. Despite this fact, we do find similar results across all participants and are still able to demonstrate statistically significant findings. Second, only young females were tested in the present study. Thus, these results may not extrapolate to younger men or older adults of either gender. Future work should examine male participants as well as older adults of both genders. A further limitation is the use of a head-free gaze registration system with a moderate spatial and temporal resolution (120 Hz). Such system does not allow detection of very fast or precise movements. However, the aim of the study was to detect gaze shift from one fixation point to another and for that purpose the instrumentation was sufficient in our view. The system is adequate for applications of medium resolution and is comparable to other currently used systems (for reliability and precision testing see Ciger et al. 2004).

Nonetheless, we propose the lack of saccades in this study is because central vision is not always required for obstacle avoidance despite short ARTs. Although recent experiments have indicated that vertical saccadic reaction time can occur within 150 ms when visual information of the fixated target is required (Trottier and Pratt 2005), it is possible that temporal constraints make saccades to track the obstacle difficult when the ART is short (i.e. ~ 219 ms). This certainly seems to be the case as the avoidance reaction (ipsilateral biceps femoris muscle activity) is initiated rapidly. However, there is sufficient time for saccadic eye movements directed to the landing area for facilitation of foot placement following obstacle clearance. While infrequent, saccades were always geared towards the landing area past the obstacle, which may partially explain the delay in saccade initiation. Safe foot placement is essential to ensure the falling center of mass of the body caused by the step is 'caught' by re-establishing a stable base of support. Thus, central vision of the landing area may be more important than actually tracking the obstacle. However, with such few saccades present in this experiment peripheral vision of the landing area is clearly sufficient. Re-direction of visual fixation was made to the landing area in compensatory stepping reactions following platform translation as well (Zettel et al. 2005), albeit infrequent, and Patla and Vickers (1997) have shown when the ART is long information regarding the obstacle is acquired in the steps before crossing but peripheral vision of the obstacle and crossing limb is sufficient to perform the task: fixations are directed to the landing area during the cross-over step. This has been supported more recently by Di Fabio et al. (2003a). Interestingly, in a later study with older adults Di Fabio et al. (2005) reported a reduction in the frequency of down saccades in high-risk cognitively challenged older adults initiating obstacle step-over. Hence, the amount of down saccades needed for crossing obstacles is likely to depend heavily on the sensory and motor abilities of the individuals involved.

The temporal organization between the initiation of the avoidance reaction and the vertical saccade was such that they are likely two independent events. In fact, saccades (which were initiated simultaneously with head pitch) were delayed, on average, by approximately 350 ms. The visuo-motor processing delay between the visual stimulus and the motor response (as reflected in the onset of the ipsilateral biceps femoris muscle) in our task was approximately 130 ms, which closely resembles that of other studies. For example, the processing delay for pointing movements ranges from approximately 114 to 201 ms (change in kinematics; Day and Lyon 2000; Whitney et al. 2003) and from 100 to 120 ms for stepping movements (change in kinematics, onset of muscle activity, and foot acceleration, respectively; Patla et al. 1991; Reynolds and Day 2005a; Weerdesteyn et al. 2004).

It remains for future research to establish whether more complex and challenging obstacles or landing places induce a higher proportion of saccades to these structures.

Conclusions

There were few saccadic eye movements for re-directing visual fixation to a suddenly appearing obstacle in the travel path. When present, eye movements occurred independent of muscle activity guiding limb movement over the obstacle (i.e. delay of ~ 350 ms) and were directed towards the landing area. Therefore, peripheral vision of a suddenly appearing obstacle in the travel path is sufficient for successful obstacle avoidance: visual fixation is generally not re-directed to either the obstacle or landing area. This is a particularly important skill for adaptive locomotion in an environment where many visual distractions are present, which make constantly attending to the ground terrain challenging.

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