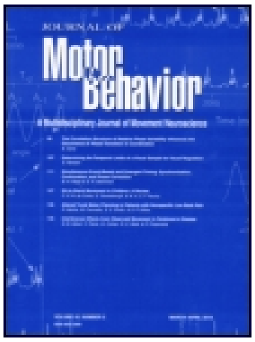

Journal of Motor Behavior

ISSN: 0022-2895 (Print) 1940-1027 (Online) Journal homepage: https://www.tandfonline.com/loi/vjmb20

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To cite this article: Sander E. M. Jansen , Alexander Toet & Peter J. Werkhoven (2010) Obstacle Crossing With Lower Visual Field Restriction: Shifts in Strategy, Journal of Motor Behavior, 43:1, 55-62, DOI: 10.1080/00222895.2010.533593

To link to this article: https://doi.org/10.1080/00222895.2010.533593

Journal of Motor Behavior, Vol. 43, No. 1, 2011

RESEARCH ARTICLE

Obstacle Crossing With Lower Visual Field Restriction: Shifts in Strategy

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ABSTRACT. In this study, the authors investigated how restriction of the vertical viewing angle influences obstacle-crossing behavior. Twelve participants stepped over obstacles of different dimensions while wearing visual-field-restricting goggles. Using full-body motion capture, several kinematic measures were extracted and analyzed. Results indicate that both a 40° and 90° vertical viewing angle yielded increased step length and toe clearance as compared to an unrestricted view (i.e., 135°), whereas speed remained unaltered. A further decrease (to 25°) caused participants to slow down in addition to a further increase of step length and toe clearance. These results are discussed in terms of a change in priorities, from conservation of energy and time to safety.

Keywords: lower visual field restriction, motion capture, obstacle crossing, strategy shifts

A common, everyday activity for humans is to walk through an environment while avoiding collisions with obstacles. One way to achieve collision-free locomotion is to step over an obstacle situated in the pathway. To ensure safe and efficient locomotion, this obstacle crossing requires visual guidance both before and during the execution of the maneuver. From an information-processing point of view, this task can be divided into the following subtasks: first, the dimensions of the obstacle have to be estimated to decide whether it is feasible (i.e., safe, comfortable, and efficient) to step over the obstacle or some other avoidance strategy is necessary (e.g., circumvention); second, a strategy must be devised to decide how the action will be executed—depending on the distance from the obstacle, a change in speed or step length may be required during the approach; third, during the execution of the maneuver, the movement needs to be updated in order to deal with perturbations in the limb trajectory caused by any initial misperception of the obstacle's dimensions and position as well as by any balancing problems.

Several studies have investigated lower limb kinematics during obstacle crossing (Chou & Draganich, 1997, 1998; McFadyen & Winter, 1991). Specifically, Patla and Rietdyk (1993) revealed that limb trajectory is substantially modulated for height changes but minimally for the width of an obstacle. They proposed three strategies that minimize the danger of tripping. First, adequate toe clearance is critical. Second, reduced forward velocity of the toe permits minimal stability threats in case of contact with the obstacle. Third, by positioning the center of mass further back (close to the stance limb) during obstacle crossing, balance is increased, which is beneficial in case of a trip. They reported increased toe clearance with obstacle height. This is in accordance with results of Chen, Ashton-Miller, Alexander, and Schultz (1991), who further reported that older participants exhibited a more conservative strategy by slowing down and shortening their step length in comparison with younger participants. However, they did not find a difference in toe clearance between the age groups.

During obstacle crossing under naturalistic viewing conditions (i.e., without restrictions), some of the visual information needed for the task is gathered by fixating on the object during the approach. This (exteroceptive) information is used in a feed-forward manner and can be used to judge the position and size of the obstacle. However, information concerned with the body relative to the environment can be perceived through the peripheral visual system and is used to update movement during obstacle crossing (Patla, 1997).

When unrestricted, the human field of view (FoV) has an average horizontal angle of 200° and an average vertical angle of 135° (Werner & Rossi, 1991). However, FoV can be restricted for several reasons, such as eye disease (e.g., retinitis pigmentosa, glaucoma) or when wearing FoV-limiting devices such as head-mounted displays (HMDs) or night vision goggles (NVGs). Even an everyday activity such as carrying a tray or other large object causes occlusion of part of the lower visual field.

Early studies have shown that restriction of FoV impairs everyday functioning (Alfano & Michel, 1990; Dolezal, 1982). Specifically, the distance to targets on the ground is underestimated when the visual field is restricted (Watt, Bradshaw, & Rushton, 2000; Willemsen, Colton, Creem-Regehr, & Thompson, 2009). Furthermore, FoV restriction has been shown to disturb the maintenance of postural equilibrium (Amblard & Carblanc, 1980; Paulus, Straube, & Brandt, 1984; Turano, Herdman, & Dagnelie, 1993) as well as the ability to control heading (Patterson, Winterbottom, & Pierce, 2006).

Also, observers tend to compensate for the reduction in their instantaneous visual field by making extensive head movements (Kasper, Haworth, Szoboszlay, King, & Halmos, 1997; Wells & Venturino, 1990). According to Rieser, Hill, Talor, Bradfield, and Rosen (1992), early experience with a large visual field is required to create and maintain an accurate representation of the world, which is assumed by some to be used during perceptuomotor tasks. It has been proposed that optic flow is used to guide this behavior (Warren, Kay, Zosh, Duchon, & Sahuc, 2001). In contrast, it is argued that visual guidance of locomotion is achieved not by optic flow,

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but by keeping targets and obstacles at fixed angles, or eccentricity, relative to the body (Rushton, Harris, Lloyd, & Wann, 1998; Rushton, Wen, & Allison, 2002).

Moreover, much of the research concerning FoV restriction has focused either on the horizontal angle of the visual field or on circular restriction. However, in the last decade there have been studies investigating the effects of the vertical extent of the visual field on perceptuomotor tasks. Wu, Ooi, and He (2004) observed impaired performance of distance estimation when the lower visual field was blocked, and found that values returned to normal when participants were allowed to make head movements. Additionally, a number of researchers investigated the influence of the lower visual field on obstacle-crossing behavior (Mohagheghi, Moraes, & Patla, 2004; Patla, 1998; Patla, Davies, & Niechwiej, 2004). Specifically, Patla reported an experiment in which participants stepped over obstacles without information from the lower visual field. He found increased toe clearance as a consequence of this visual impairment and concluded that this is caused by the lack of visual information needed to fine-tune the lower limb trajectory. Following this, Rietdyk and Rhea studied the effects of exproprioceptive (sight of own limbs) and exteroceptive (cues in the environment) information on obstacle crossing(Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006).

Similarly to Patla (1998), they concluded that information about obstacle position and size is used in advance to plan a maneuver, whereas information about the body relative to the obstacle is used to control and update movement during the execution. In addition to lower body kinematics, several researchers have investigated gaze behavior during obstacle crossing: Patla and Vickers (1997, 2003) identified two dominant gaze behaviors during adaptive locomotion: landing target fixation and travel gaze fixation. They argued that the latter is more dominant and consists of the eyes being directed at the ground ahead and not to a specific location. Marigold and Patla (2008) and Marigold, Weerdesteyn, Patla, and Duysens (2007) examined the lower body kinematics and gaze behavior of participants when stepping over obstacles that suddenly appeared in the pathway. Downward-directed saccades were rarely made and when present were directed to the landing area not the obstacle. The conclusion was that peripheral visual information is sufficient for safe obstacle negotiation.

They further reported an increased head pitch angle as well as an altered gait speed and step length when 30–40° of the lower visual field was blocked. Moreover, in a recent review article, Marigold (2008) stressed the importance of the lower visual field for online visual guidance of locomotion.

In a similar manner, recent studies conducted by Graci, Elliott, and Buckley (2009, 2010) investigated the effects of peripheral visual field restriction on overground locomotion and on stepping over an obstacle. They found increased toe clearance and stride length for a lower visual field occlusion as well as for a circumferential occlusion when stepping over low obstacles (4–8 cm high).

Although some work has been done to investigate the influence of the lower visual field on obstacle avoidance and locomotion, studies examining the effects of different levels of viewing restriction are sparse. Previous work investigating this showed that a decrease of both the horizontal (Toet, Jansen, & Delleman, 2007, 2008) and vertical viewing angle (Jansen, Toet, & Delleman, 2010; Toet, van der Hoeven, Kahrimanović, & Delleman, 2008) affects maneuvering performance while traversing an obstacle course consisting of multiple obstacles. It is argued that the vertical angular extent is more dominant for local obstacle avoidance tasks. For example, a visual field of $80^\circ \times 40^\circ$ can be enlarged by increasing either the horizontal or vertical extent. It was shown that an enlargement of the vertical angle by 20° constitutes a greater performance increase (of traversing an obstacle course) when compared to an enlargement of 35° of the horizontal angle.

By interpreting the kinematic measures, it is possible to shed some light on the behavioral strategies that are employed. Several researchers argued that unobstructed walking is characterized by an energy conservation strategy (Anderson & Pandy, 2001; Inman, 1966; Mochon & McMahon, 1980; Saunders, Inman, & Eberhart, 1953; Waters & Mulroy, 1999). More specifically, it has been estimated that 67% of the total energy used for locomotion is due to passive energy transfers between segments (Pierrynowski, Winter, & Norman, 1980). As opposed to unobstructed walking, during obstacle crossing, safety becomes a concern. Patla, Prentice, Robinson, and Neufeld (1991) argued that to ensure safe crossing, a certain clearance has to be taken into consideration. Additionally, the velocity of the center of mass is reduced to minimize injury in case of a collision. In the present experiment we investigated how this strategy changes as a result of restricted viewing conditions. We expected that a reduced vertical viewing angle would cause a shift in priority from energy-conservative and time-efficient strategies to behavior emphasizing safety. As a result, we hypothesized that step length and toe clearance would be increased during obstacle crossing. The same was expected for maximum head pitch during the approach phase. Furthermore, we expected a decrease in the average speed with which this task would be performed. Additionally, we investigated how trail limb clearance is modulated as a result of a restricted vertical view. This is interesting because the trail limb is never visible during obstacle crossing. Therefore, modulation as a result of this viewing manipulation may be interpreted as a holistic behavioral shift to emphasize safety. A full-body motion capture system was used to gather kinematic data during the crossing of obstacles of different dimensions.

Method

Participants

The procedures of this study were approved by the TNO (the Netherlands Organisation for Applied Science

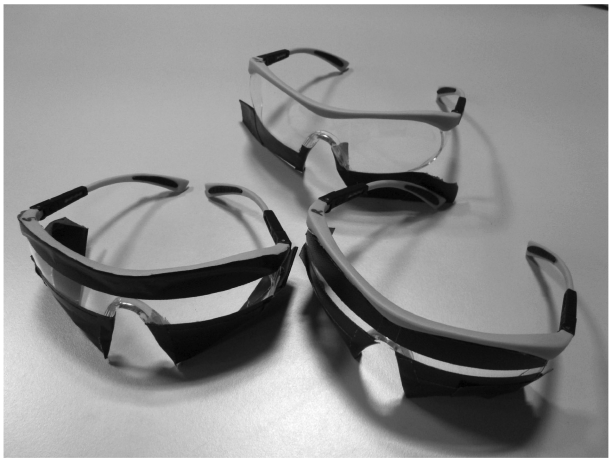

FIGURE 1. Goggles used to restrict the vertical viewing angle while leaving the horizontal extent unrestricted.

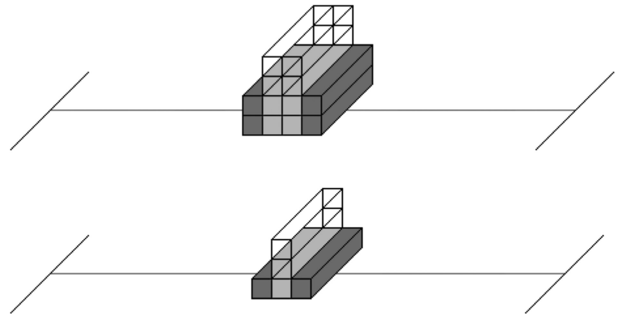

FIGURE 2. The four obstacle configurations situated in the pathway. Black lines indicate the start and end position for each trial. Both the large and small obstacles are shown in upright (transparent) and recumbent (gray) orientations.

Research) Human Factors internal review board on experiments with human participants. Twelve participants (6 men and 6 women) ranging in age from 19 to 39 years ($M = 25.2$, $SD = 4.9$) took part in the experiment and gave informed consent. All were free of any known neurological or orthopedic disorders, or any impediments to normal locomotion. Furthermore, all participants had normal or corrected-to-normal vision as verified by self-report.

Apparatus

Goggles

For each viewing condition, an unrestricted horizontal angular extent was combined with each of four vertical viewing angles. This set of vertical visual angles was chosen to incorporate a small condition (25°) as well as a commonly used angle in HMDs (40°), a large angle (90°), and an unrestricted condition (135°). A separate pair of safety goggles was used for each of these conditions (of the type Bollé Targa; http://www.bolle-safety.com; see Figure 1). Part of the lens was covered with duct tape in such a way that a restriction of the vertical angular extent was induced without altering the horizontal angle. Because of variation in bone structure, the exact visual angle varied slightly per participant. However, because we used a within-subjects design, this did not alter any possible conclusions drawn from the data.

Motion Capture System

Full-body motion was captured using the MVN motion capture system by XSens (http://www.xsens.com, Enschede, the Netherlands). Participants wore a Lycra suit equipped with 17 sensory modules, containing three-dimensional gyroscopes, accelerometers, and magnetometers. Using the Xsens software, participants' full-body motion was recorded for each trial with an update rate of 100 Hz. A sensor fusion scheme calculated the position, velocity, acceleration, orientation, angular velocity, and angular acceleration of each body segment, with respect to an Earth-fixed reference coordinate system. For a more extensive description of this system, see Roetenberg, Luinge, and Slycke (2009).

Obstacle

During each trial, participants stepped over a single obstacle placed exactly halfway between the start and end positions, which were indicated by markings on the floor. Two separate obstacles were used, each in two different configurations, resulting in a total of four obstacle conditions. Height and depth dimensions were 280 × 140 mm for the larger obstacle and 210 × 70 mm for the smaller obstacle. A schematic illustration of the setup is in Figure 2.

Design and Procedure

A 4 (Vertical Angular Extent) × 4 (Obstacle Size) full factorial design was used, resulting in 16 conditions. Using a Latin square (Wagenaar, 1969), conditions were randomized across trials and performed three times each. In total, each participant performed 48 trials.

After filling out the informed consent form, participants put on the Lycra suit containing the sensors. Before starting the experimental session, a calibration procedure was performed in which the sensor to body alignment and body dimensions were determined. First, body height and foot size were measured. Using regression equations based on anthropometric models, other dimensions were obtained as well. Second, a calibration procedure was performed. The rotation from sensor to body segment was then determined by matching the orientation of the sensor in the global frame with the known orientation of each segment in a specific pose. For further reading about this process, see Roetenberg et al. (2009).

During the experimental session, participants were instructed to walk at a comfortable, self-preferred pace from the start to end positions while avoiding contact with the obstacle. After the third trial of each condition was performed, the experimenter changed the obstacle arrangement and viewing condition in accordance with the next condition. All conditions were performed consecutively without interruption. During the entire experimental session, full-body motion was recorded at a sampling rate of 100 Hz. This rate is in accordance with recent work involving foot placement (Rietdyk & Drifmeyer, 2009).

Dependent Variables

The MVN motion-capture system outputs three-dimensional position of 23 body segments using a biomechanical model (Roetenberg et al., 2009). With the use of Matlab (Guide, 1998), several dependent measures were extracted for each trial. First, step length was calculated as the Euclidean distance between the lead-limb toe and the trail-limb toe at the moment the lead limb touches the floor. Second, max lead and trail-limb clearance were defined as the maximum height of the toe during obstacle crossing for the lead and trail limbs, respectively. Obstacle height was subtracted from this to remove the systematic increase. Third, the maximum head pitch was calculated as the maximum angular offset from looking straight ahead. Finally, average speed was calculated over a 4 s interval centered around the moment of contact between lead-limb toe and floor. By taking the Euclidean distance between the position of the chest at the start and end of this interval, the average speed was calculated. Figure 3 gives a schematic representation of the spatial variables.

Statistical Analysis

Although each condition was tested three times, only the final two trials were analyzed. This was done to counter possible learning effects. In order to be clear, these two trials are referred to by their initial numbers (i.e., two and three). Overall, this resulted in a 4 (Vertical Angular Extent) × 4 (Obstacle Size) × 2 repeated measures analysis of variance (ANOVA) for each of the dependent measures (i.e., step length, lead and trail clearance, maximum head pitch, and average speed). Whenever Mauchley's test indicated a violation of the sphericity assumption, a Greenhouse–Geisser correction was applied to the variance analysis as well as a Bonferroni adjustment on the pairwise comparisons (Field, 2009). All analyses were performed with STATISTICA 8.0 (StatSoft, 2007) and significance levels for each were set to 5%.

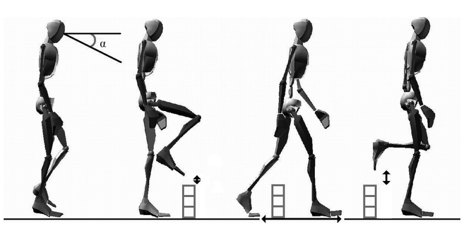

FIGURE 3. The spatial variables analyzed in this study. From left to right: maximum head pitch angle, lead limb clearance, step length, and trail limb clearance.

Results

Step Length

There is an effect of vertical viewing angle on step length while stepping over an obstacle, $F(3, 33) = 21.299, p < .001$. A decrease in viewing angle led to an increase in step length (Figure 4). Pairwise analysis shows significant differences between each of the viewing conditions except between 40° and 90° ($p = .12$), for all others $p < .001$. Step length was not affected by obstacle type. Furthermore, the analysis shows no difference between the two trials. Moreover, no interaction effects were found.

Toe Clearance

Lead Limb

The extent of the vertical viewing angle affects lead limb clearance, $F(3, 33) = 18.313$, $p < .001$. A decrease in viewing angle yielded an increase in lead limb clearance. Pairwise comparison shows significant differences between each of the viewing conditions except between 40° and 90° ($p = .12$), for all others $p < .05$. Furthermore, there was an effect of obstacle type on lead limb clearance, $F(3, 33) = 16.781$, $p < .001$. Pairwise analysis showed that toe clearance was smaller for the shortest obstacle (i.e., 70 × 210 mm)

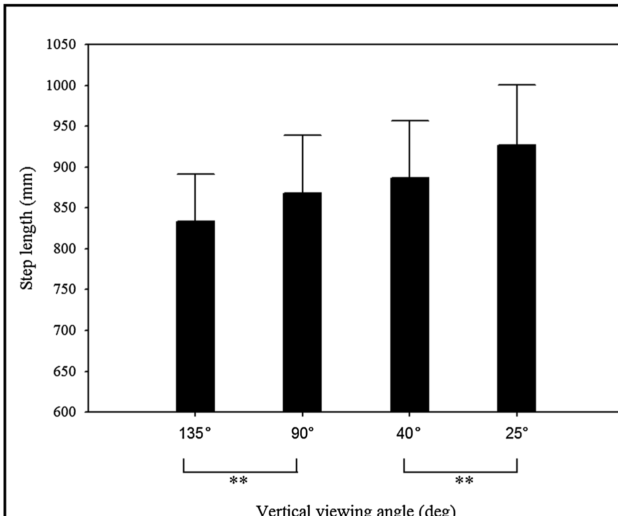

FIGURE 4. Step length as a function of vertical viewing angle. Significant results of pairwise comparison for the main effects are illustrated by *($p < .05$), **($p < .01$), and ***($p < .001$). Error bars represent standard error.

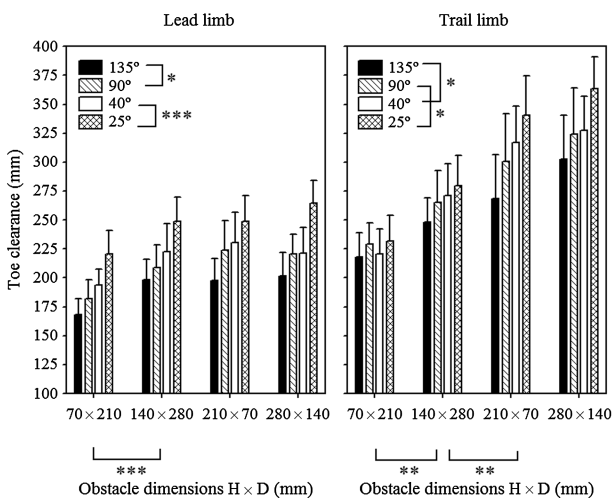

FIGURE 5. Toe clearance as a function of viewing condition and obstacle type. Lead and trail limb clearance are shown left and right, respectively. Significant results of pairwise comparison for the main effects are illustrated by *($p < .05$), **($p < .01$), and ***($p < .001$). Error bars represent standard error.

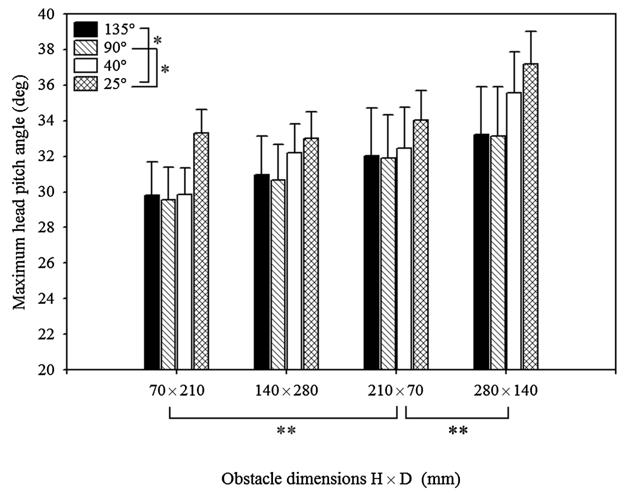

FIGURE 6. Maximum head pitch angle as a function of viewing condition and obstacle type. Significant results of pairwise comparison for the main effects are illustrated by *($p < .05$), **($p < .01$), and ***($p < .001$). Error bars represent standard error.

compared to the other types (all ps $< .001$). No difference was found between the two trials, and there were no interaction effects. See the left-hand graph in Figure 5 for the data.

Trail Limb

Trail limb clearance was affected, in a similar manner as that of the lead limb, by the extent of the vertical viewing angle, $F(3, 33) = 5.726$, $p < .01$. A pairwise comparison revealed significant differences between the smallest visual angle (25°) and the 135° ($p < .001$) and 90° ($p = .03$) conditions as well as between 40° and 135° ($p = .03$). Additionally, there was an effect of obstacle type on trail limb clearance, $F(3, 33) = 21.642$, $p < .001$. Trail limb clearance differed for all obstacle types, except between the 210 × 70 mm and the 280 × 140 mm configurations ($p = .11$, for all other comparisons ps $< .01$). Furthermore, no interaction effects were found between viewing condition and obstacle type, and there was no difference between the two trials. See the right-hand graph in Figure 5.

Maximum Head Pitch

The extent of the vertical viewing angle had an effect on the maximum head pitch angle during the approach to the obstacle, $F(3, 33) = 4.740$, $p < .01$. A pairwise comparison shows that the smallest angle of 25° yields increased pitch compared to the 135° ($p = .02$) and 90° ($p = .01$) conditions. Furthermore, there was an effect of obstacle type on maximum head pitch angle, $F(3, 33) = 14.771$, $p < .001$. Downward pitch was increased for the tallest obstacle (280 × 140 mm) compared to all others ($p < .01$). Also, the 210 × 70 mm configuration caused increased pitch compared to the shortest (70 × 210 mm) obstacle ($p < .01$). See Figure 6 for the data. Additionally, we found that head pitch angle increased during the third trial of a condition as compared to the second, $F(1, 11) = 8.286$, $p = .02$. No interaction effects were found.

Average Speed

Decreasing the vertical viewing angle resulted in a decrease in average speed, $F(3, 33) = 5.934$, $p < .01$. Specifically, the smallest angle (i.e., 25°) caused slower movement than any of the other conditions (ps $< .01$). Additionally, there was an effect of obstacle type on speed, $F(3, 33) = 42.643$, $p < .001$. All conditions differed from each other except the 70 × 210 mm and 140 × 280 mm configurations ($p = .15$, for all others $p < .01$). Figure 7 shows the data. Overall, speed was decreased for the third trial as compared to the second, $F(1, 11) = 10.505$, $p < .01$. Moreover, an interaction effect was found between viewing condition and trial number, $F(3, 33) = 4.440$, $p < .001$. For viewing angles 135°, 40°, and 25°, the third trial was slower than the second one. However, for the 90° condition the opposite was true. Furthermore, no interaction effect between viewing condition and obstacle type was found.

Discussion

The results of this study indicate that restriction of the vertical viewing angle affected lower body kinematics during obstacle crossing. Specifically, decreasing the vertical viewing angle affected step length and lead limb clearance

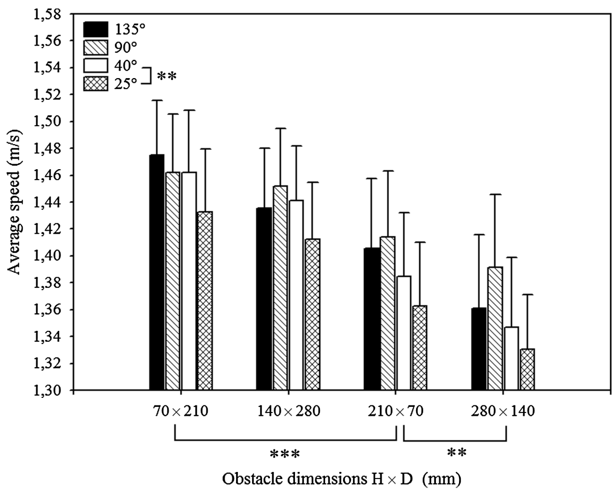

FIGURE 7. Average speed as a function of viewing condition and obstacle type. Significant results of pairwise comparison for the main effects are illustrated by *($p < .05$), **($p < .01$) and ***($p < .001$). Error bars represent standard error.

in a similar manner. Unrestricted (e.g., with a 135° view), participants crossed the obstacle at a preferred speed while employing the lower limb kinematics that they favored. When confronted with an intermediate (40–90°) view, step length and lead limb clearance increased. Likewise, with a 25° view, the smallest visual angle tested here, step length and lead limb clearance increased even more. Investigation of the average speed during obstacle crossing revealed that only the smallest visual angle resulted in a decreased speed. This finding is in accordance with previous work (Jansen et al., 2010) showing that a vertical viewing angle of 25° yielded decreased speed during traversal of an obstacle course as compared with larger angles.

With an unrestricted view, there is a minimal risk of tripping. Therefore, it is likely that priority is given to minimize energy expenditure and maximize time efficiency. Applying such a strategy resulted in small lead limb clearance and step length while moving at a preferred speed. When performing the obstacle-crossing task with an intermediate vertical angle (40–90°), the decrease in visual information from the lower visual field caused the lead limb and obstacle to be invisible during the actual crossing of the obstacle. This may pose a threat to safety because possible perturbations in the limb trajectory (caused by misperception of obstacle dimensions and position as well as balancing problems) cannot be perceived and therefore acted on. As a result, it seems the strategy was altered to give priority to the prevention of tripping instead of the minimization of energy and time. As a consequence, step length and toe clearance increased. Surprisingly, under these viewing conditions the average speed remained unaltered. Moreover, when confronted with the smallest visual angle (i.e., 25°), safety becomes even more compromised. This resulted in further increases in step length and lead limb clearance. In this case, however, the average speed was also altered. This can be explained as the increased priority of safety at the cost of energy and time considerations. Judging from the results, it seems that for a simple obstacle-crossing task, time efficiency has priority over energy conservation. This is concluded from the observation that the latter was sacrificed first as a consequence of compromised safety and only after additional reduction of the vertical viewing angle did we observe a decrease in speed.

As a result of vertical viewing restriction, trail limb clearance increased in a similar manner to that of the lead limb. This is in accordance with previous findings, which show a correlation between the elevation of both limbs when there is no online visual information available (Patla et al., 2004). However, under full cue conditions, lead and trail limb have been shown to be independently controlled (Patla, Rietdyk, Martin, & Prentice, 1996). The fact that viewing restriction modulates trail limb clearance is interesting because the trail limb is never visible during obstacle crossing. Therefore, the increased clearance cannot be the direct cause of impaired vision of the limb during execution of the maneuver. Instead, it seems that the overall strategy to prioritize safety over energy conservation and time efficiency is a holistic approach.

When looking at the maximum head pitch angle, we saw an increase in pitch as a result of vertical viewing restriction. But significant differences were only found between the smallest viewing angle (i.e., 25°) and both 90° and 135°. This indicated that a vertical angle of 40° was sufficient to update information regarding the body relative to the obstacle position, and there was no need for extensive head pitch movement in the approach phase. Only when the angle is very small is there a need for increased downward pitch movement during the approach phase. Furthermore, during none of the restricted viewing angles was the lead limb visible during obstacle crossing. The increase in downward pitch seen with smaller angles did not change this. Instead, we argue that the increase in toe clearance and step length is a way of ensuring safety when there's no visual information concerning the obstacle and the lead limb during obstacle crossing.

Surprisingly, we found that average speed and maximum head pitch angle differed between the two trials analyzed for each condition. The later trial yielded slower movement and increased pitch compared with the earlier one. We do not have a good explanation for these sequence effects. Also, we did not find similar results for the other dependent variables. Future researchers should examine if this sequence effect is caused by something like fatigue, which is in itself an interesting manipulation to investigate in light of strategy changes.

When discussing the influence of obstacle type, it should be noted that the dimensions were not manipulated independently (height covaries with depth); therefore, it is not possible to draw inferences concerning either height or depth. Nevertheless, it seems that larger obstacles (in the sense of volume) cause increased toe clearance of both the lead and trail limbs compared to smaller obstacles. Conversely, we found no difference in step length as a result of obstacle type. This is in accordance with previous findings (Chen et al., 1991; Patla & Rietdyk, 1993). Furthermore, it seems that larger obstacles yielded increased head pitch angle and decreased speed compared to smaller obstacles.

In conclusion, our results agree with several studies reporting increased toe clearance and step length combined with decreased speed as a consequence of lower visual field occlusion (Graci et al., 2009, 2010; Marigold & Patla, 2008; Mohagheghi et al., 2004). The important difference is that we investigated several levels of visual field restriction, which enables the observation of shifts in strategy as viewing conditions deteriorate. Several factors can be the cause of visual field restriction. Some of these are involuntary (e.g., eye disease), whereas others are the consequence of choices individuals make. An example of this latter category is the selection of visual-field-restricting hardware, such as HMDs and NVGs. In such cases it is useful to know the influence of FoV restriction on human behavior to select the right hardware for a specific task. For instance, HMDs are frequently used for training and rehearsing tasks in virtual environments that involve human locomotion through complex structured environments (e.g., dismounted soldiers, first responders). A central issue in the design and selection of HMDs is the size of the visual field. Many commercially available HMDs afford the user a vertical angle of 30–50°. We have shown that even for an isolated simple task such as the one presented here, motor behavior changes as a result of such a hardware choice. This could have implications for the transfer of skills from virtual to real environments.

It should be noted that the strategy shifts observed here hold only for this specific task and (experimental) conditions. We cannot conclude that other environmental circumstances yield the same strategy shifts. For instance, when the consequence of tripping becomes more severe (e.g., when running), it may very well be that time efficiency is sacrificed immediately as a result of an increased risk of tripping. Future researchers should investigate if the strategy shift found here also holds for other maneuvering tasks and under other suboptimal conditions. An example of this is the effect of impaired lighting conditions on obstacle avoidance behavior. Furthermore, it would be useful to investigate if the existence of the 40–90° plateau that we found here can be replicated in other situations. Finally, it would be interesting to investigate how certain predispositions in people or specific instructions alter the strategies used during obstacle avoidance.

ACKNOWLEDGMENTS

The authors wish to thank Koen Tan for his suggestions and assistance with MATLAB analyses and Annemarie Levert for supervision during the experimental sessions. This research has been supported by the GATE project, funded by The Netherlands Organization for Scientific Research (NWO) and The Netherlands ICT Research and Innovation Authority (ICTRegie).

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Submitted March 15, 2010
Revised July 1, 2010
Second revision August 18, 2010
Third revision October 13, 2010
Accepted October 13, 2010