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When an object appears unexpectedly: object circumvention in adults

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Abstract
Obstacles often appear unexpectedly in our pathway and these require us to make immediate adjustments. Despite how regularly we encounter such situations only few studies have considered how we adjust to unexpected obstacles in the pathway which require us to walk around them. The current study considered how adults adjust to the possibility of an obstacle appearing and then also how foot placement is adjusted to circumvent an obstacle. Fifteen healthy adults walked down an 11m walkway, initially they were told this was a clear pathway and nothing in the environment would change (no gate), they then performed a series of trials in which a gate may (gate close) or may not (gate open) partially obstruct their pathway. We found that medio-lateral trunk velocity and acceleration was significantly increased when there was the *possibility* of an obstacle but before the obstacle appeared. This demonstrates an adaptive walking strategy which seems to enable healthy young adults to successfully circumvent obstacles. We also categorised foot placement adjustments and found that adults favoured making shorter and wider steps away from the obstacle. We suggest this combination of adjustments allows participants to maintain stability whilst successfully circumventing the obstacle.

Keywords
Trunk velocity, trunk acceleration, obstacle circumvention, avoidance

1. Introduction

As part of everyday life we need to negotiate obstacles as we locomote through the environment. The ability to avoid static and moving objects is vital for our safety and efficient passage. An examination of how this is achieved in healthy adults provides information on how such movements are planned and controlled. When confronted with an obstacle a walker needs to adjust and control movement in order to avoid that obstacle, for example if such an obstacle is at ground level this may involve side stepping or stepping over.

When approaching a stationary object which has been present in the pathway walkers are able to use a pre-planned movement strategy to avoid collision (de Silva, Barbieri, & Gobbi, 2011; Higuchi, 2013; Huxham, Goldie, & Patla, 2001; Patla & Vickers, 2003). Studies concerning the stepping over of stationary obstacles have shown that foot placement is adjusted according to task demands and this allows an optimal take-off position (Krell & Patla, 2002), a stepping over movement is planned at least one step prior to the execution of that movement (Patla, 1998) and a greater clearance between foot and obstacle is given when stepping over a fragile object (Patla, Rietdyk, Martin, & Prentice, 1996). Furthermore, studies focusing on how adults circumvent an obstacle in their pathway have described a number of avoidance strategies. For example Vallis & McFadyen (2003) asked participants to walk up to and around an obstacle. Participants naturally adopted two different strategies a 'lead-in strategy' where the lead foot moves towards the obstacle and a 'lead-out strategy' where the lead foot moves away from the obstacle. The authors compared trials across these strategies to see whether they resulted in any difference in kinematics of obstacle avoidance. The two strategies were used equally and participants did not favour one or the other. Both walking speed and step width at obstacle circumvention were different across strategy, with the lead-out strategy being slower than the lead-in. In terms of step-width, three and two steps away from the obstacle the lead-in strategy involved a wider step width than the lead-out strategy but one step away from the obstacle the lead-out strategy involved the wider step width. The fact that participants started their alternative foot placements two or three steps prior to reaching the obstacle demonstrates a clear pre-planning and anticipatory control when avoiding stationary obstacles.

The studies described above have considered the navigation of a static obstacle; when the participant starts to walk the obstacle is in the pathway and remains in the same position throughout each trial. Although we do navigate obstacles such as this in our everyday life (e.g. static street furniture), on many occasions we need to navigate obstacles that unexpectedly move into our path of travel (e.g. a pedestrian appearing from an adjoining road, a ball rolling across our path). These types of scenarios require more of a reactive walking strategy (Higuchi, 2013). A number of cleverly designed studies have examined how healthy adults avoid obstacles which unexpectedly appear on the pathway in front of them (Chen, Ashton-Miller, Alexander, & Schultz, 1994; Patla, Beuter, & Prentice, 1991; Patla, Prentice, Rietdyk, Allard, & Martin, 1999; Weerdesteyn, Nienhuis, Hampsink, & Duysens, 2004). The common finding across these studies is that participants are able to adjust their movement and react to an obstacle appearing suddenly, many of these studies documented the strategies used by participants in successfully avoiding collision. However, in all of these studies participants are expecting an obstacle to appear but they don't know when. We know from studies where an obstacle is in the pathway throughout approach that participants may reduce walking velocity and step length when approaching an obstacle, which may allow more time for necessary adjustments (Chen, Ashton-Miller, Alexander, & Schultz, 1991; Chou & Draganich, 1997; MCfadyen & Carnahan, 1997). This raises the question as to whether participants, when knowing an obstacle may appear in their pathway, adjust their movement in order to prepare for any upcoming adjustments.

A handful of studies have considered this very question, however, these do not focus on obstacle avoidance but are described here as they are the only examples of this type of paradigm. Pijnappels, Bobbert, & van Dieën (2001) compared the kinematics of walking under two conditions, unobstructed walking and walking when participants were warned that a trip may be induced (forewarning). Participants made no changes to the temporal parameters of walking (velocity, step frequency, swing time double support time), however, they did show an increase in step width during forewarning (5.3% widening of the step). Given the small changes from the unobstructed walking to the forewarning condition (Pijnappels et al., 2001) concluded that although there were clear anticipatory changes, that these would not help to reduce the possibility of a trip or indeed to help with recovery if a trip did occur. In a similar vein, Pater, Rosenblatt, & Grabiner (2015) also considered anticipation of a fall while walking on a treadmill, while participants walked a perturbation could be introduced, whereby the speed of the treadmill suddenly increased. One group of participants were warned about this perturbation (expectation group) while another were not (no expectation group). The expectation group fell less often following the perturbation compared to the no-expectation group and the recovery (in terms of the kinematics of the step following the trip) of the expectation group was classified as more typical than the no-expectation group. Finally, Potocanac et al. (2014) induced a trip, however they also had a 'forbidden zone' which participants were told they could not step on following the trip. The study started with a number of simple 'trip' trials, following this came the 'trip and forbidden zone' trials and in this second block there were some 'trip only' trials (catch trials). In essence, a comparison of the 'trip' trials and the 'catch' trials allows us to look at anticipatory behaviour (anticipation of the presence of the forbidden zone). Potocanac et al. (2014) found that the catch trials had a shorter duration and that their foot landed much further from the typical placement of the forbidden zone compared to the trip trials. These studies provide an important insight into anticipatory behaviour and clearly show some modification of behaviour. However, these studies have all looked at a high harm (tripping) situation. From these studies it is unclear whether this type of anticipatory behaviour is only used when the potential for harm is high. To our knowledge there are no examples of this type of anticipatory movement in response to the possibility of an obstacle appearing.

Within obstacle avoidance paradigms, once the obstacle is apparent (and regardless of whether it appeared unexpectedly or not) is the issue of how such an obstacle is navigated. A number of studies have considered how and where participants place their feet when making adjustments following obstacle appearance. Patla et al. (1999) set up a study where they asked participants to walk along a designated path and if a light spot appeared on the floor they had to avoid stepping on it, which required an adjustment to the stepping pattern. Adjustments were classified into 8 strategies: long, short, medial, lateral, long medial, long lateral, short medial and short lateral. Results demonstrated that the choice of these was not random, rather participants favoured one response depending on the conditions of the trial. Participants preferred to lengthen their step in the condition where the light spot appeared where the back of the leading foot would have landed, place their foot more medially (narrowing the step width) in the condition where the spot appeared directly where the leading foot would have landed and shorten their step in the condition where the light spot appeared where the front of the foot would have landed. From their findings (Patla et al., 1999) suggested some criteria for the selection of foot placement adaptation, these were efficiency, stability and maintenance of forward progression. These criteria have been validated by a number of studies (Moraes, Allard, & Patla, 2007; Moraes, Lewis, & Patla, 2004; Weerdesteyn, Nienhuis, Mulder, & Duysens, 2005). Interestingly, it would seem that no one of these is the dominant criterion, but rather each is a single determinant in the decision process (see Moraes, 2014 for a review). Different studies have gone on to consider the situations and reasons for some choices, in terms of alternative foot placement, over others.

Chen et al. (1994) used virtual obstacles which allowed them to project a ‘to be stepped over’ obstacle onto the pathway of a group of young and elderly adults. The timing of obstacle appearance was altered to give participants more or less time to respond. Participants could either adopt a short-step over strategy or a long-step over strategy. Chen and colleagues found that as response time decreased participants tended towards using the short-step, whereas when more time was available all participants adopted the long step strategy. Weerdesteyn et al. (2005) also considered stepping over obstacles while walking on a treadmill and they found that older females prefer lengthening their strides over shortening their strides even though this was not the optimum choice in terms of minimum foot displacement (i.e. efficiency). Step lengthening has also been shown to be the preferred strategy in individuals recovering from stroke (Den Otter, Geurts, de Haart, Mulder, & Duysens, 2005). Moraes et al. (2007) in a stepping over paradigm, where the obstacle was present from the start of the trial also demonstrated a clear preference for long and lateral adjustments, a preference which the authors suggest is due to the fact that this is a more stable adaptation. Furthermore, Moraes (2014) argues that step lengthening provides more time to alter limb trajectory than step shortening which may account for this preference. From these studies it would seem that participants are biased towards maintenance of forward progression (illustrated by the preference for step lengthening) when there is adequate time to plan such adjustments, when time is short this preference is changed in order to satisfy the other criteria.

The studies described above vary in terms of exactly how long the obstacle is present before the participant needs to make any adjustments (i.e. appearing just prior to an adjustment being needed or being present from a number of meters away) and this difference has led to a greater understanding of foot adjustment. However, in the main they have only considered the ‘crossing’ step (i.e. the one that stepped over the obstacle). Given that we know from previous research that adjustments to movement can start up to two or three steps away from an obstacle (for example see Gerin-Lajoie, Richards, & Mcfadyen, 2005; Vallis and McFadyen, 2003) it is important to consider the adjustments that are used prior to the crossing step. In the current study we investigate the way in which young healthy adults circumvent an obstacle (closing gate) that occasionally and unpredictably blocks their path as they walk. The aims are two-fold: 1. To consider how these adults anticipate a possible obstacle in a low harm situation, we do this by comparing walking trials in the ‘gate close’ condition with two other conditions; a ‘gate open’ condition where there is a *possibility* that the same obstacle (a gate) will move to block the pathway (but the gate actually remains open) and a ‘no gate’ condition where there is no possibility for an obstacle to block the path; 2. To consider how adults circumvent an unpredictably appearing obstacle, we do this by considering step adjustment strategies on the four steps leading up to the gate.

2. Method

2.1 Participants

Fifteen adults[1] aged 18.6-30.4 years (mean 23.4 years) were recruited from Oxford Brookes University and the surrounding area, 8 were female and 7 male. All participants self-reported normal or corrected-to-normal vision and an absence of motor difficulties. Ethical approval for the study was granted from Oxford Brookes University Research Ethics Committee. Participants received a small payment for participation.

2.2 Apparatus and procedure

Participants were instructed to walk barefoot at a comfortable pace along an 11m by 1m walkway made from high density foam sports mats. Two rectangular gates, each 60cm wide and 30cm high and constructed from the same high density foam material, were positioned on each side of the walkway (see Fig. 1a) 8m from the start point. A motion sensor positioned 5m from the start point and 3m in front of the gates was used to trigger either the right or left gate to swing to rest across the pathway. When the motion sensor was activated there was a delay of ~16ms prior to the gate starting to move and the gate took ~1250ms to fully close.

A Vicon Nexus 3D motion capture system with 16 cameras running at 100Hz was used to track the movement of reflective spherical markers (9mm in diameter) attached to the skin at five bony landmarks: the sacral wand, the second metatarsal head on left and right foot (left and right toe marker), and the lateral malleolus on left and right foot (left and right ankle marker). Initially participants completed 6 'no gate' trials. On these trials the gates and motion sensors were present at the side of the walkway but participants were told that these were to be ignored. Participants were instructed to walk the length of the walkway at a natural pace. In each no gate trial participants were instructed to walk from the start to the stop point, and then return to the start by the return path. In 'gate close' trials the motion sensor was switched on so that it was triggered as the participant walked by, causing one of the gates to close across the pathway (Fig. 1c) and forcing them to circumvent the gate to avoid collision and continue their passage. Circumvention of a closed gate was first demonstrated to participants, who were instructed to avoid the gate while continuing their passage along the walkway. On 'gate open' trials, unbeknown to the participant, the motion sensor was deactivated so that the gates remained stationery and parallel to the walkway throughout the trial (Fig. 1b) allowing for unobstructed passage. From a participant's point of view, in the 'gate open' condition there is a *possibility* that a gate will swing closed to

[1] This sample size gives sufficient power assuming a large effect size (Faul, Erdfelder, Lang, & Buchner, 2007)

partially block the pathway. Participants completed 6 'gate close' and 30 'gate open' trials with the former interspersed randomly among the latter and the side of closure (right or left) also random, due to this random nature participants were not always presented with 3 right gate close trials and 3 left gate close trials. This ensured that presence of the obstacle in the pathway was unpredictable. The start point was varied by ±20cm to avoid the participant starting at a consistent distance from the obstacle. Participants were informed that the 'gate' may close and when that happened they were to avoid collision, no instruction was given as to exactly how participants were to avoid the gate, although the demonstration involved walking around it.

INSERT FIGURE 1 HERE

2.3 Data processing

VICON movement data was smoothed using an optimized low-pass Woltring filter with a 12 Hz cut-off point and was then processed using tailored Matlab routines. Measurements of trunk movement and foot placement were taken. For all trials movement was split into two parts: before obstacle trigger (the before phase), which is defined as the 2m between start of data capture and the sensor and after obstacle trigger (after phase) which is defined as the 3m between the sensor and the gate.

Trunk movement: Movement of the sacral marker was taken as an indicator of trunk movement. For each step sacral root mean squared velocity (ms^{-1}) and acceleration (ms^{-2}) was calculated over the three axes of movement: medio-lateral (ML); anterior-posterior (AP); and vertical (V). *Spatial parameters of foot placement:* For each trial every stride falling between the start of data capture and passing the gate was analysed. Heel strike (HS) and toe off (TO) events were determined based upon an adapted foot velocity algorithm, which was adapted in order to use an ankle rather than a heel marker (O'Connor, Thorpe, O'Malleya, & Vaughana, 2007). From the timing of the HS and TO events two measures pertaining to foot placement were determined: *Step length*: the anterior-posterior distance between the front ankle marker and the back ankle marker at each HS; *Step width*: the medio-lateral distance between the two ankle markers at each HS. For the gate close trials *Foot placement adjustments* were also described to indicate how object circumvention was achieved. The focus here was on the final step which brought the participant parallel to the gate (crossing step) and the three steps preceding this (these all fell in the 'after phase'). The change in step length/width was calculated by subtracting values in the gate close condition from those in the no gate condition, this 'change' was then expressed as a percentage to indicate the degree of adjustment made in the gate close condition to that in the no gate condition. This gave a measure of *percentage change of step length and percentage change of step width.* Following this each step was categorised as an 'adjustment step' or a 'non-adjustment step'. Adjustments steps were those where percentage change in step length / width fell outside three standard deviations of the no gate step length / width. The number of adjustment steps per participant and the absolute percentage change of adjustment steps were calculated. Finally, each adjustment step in the gate close condition only was classified into one of 8 adjustment types. Given that either the left or the right gate could open, using a medial and lateral categorisation is not appropriate as medial adjustment may on some trials move the participant towards the obstacle, while on others it moves the participant away. Therefore, adjustments were classified as taking the participant towards the object or away from the object. The 8 adjustment strategies were: long (increase in step length only), short (decrease in step length only), towards (step width took the participant closer to the obstacle), away (step width took the participant further from the obstacle), long towards, short towards, long away and short away.

2.4 Statistical Analysis

Different analyses were carried out for each main aim of the study. For the first aim, measuring how adults anticipate a possible obstacle, measures of trunk movement and spatial parameters of foot placement were considered across the three conditions (no gate, gate open and gate close) and two phases (before phase and after phase) using a 3 x 2 way repeated measures ANOVA. For the second aim, to consider how adults circumvent an unpredictably appearing obstacle, we start by considering the number of step length and step width adjustments and the percentage change in step length and step width between both gate open and gate close conditions, inclusion of both conditions allows a comparison between an adjustment condition, gate close, and a baseline condition, gate open. To do this, the number of step length and step width adjustments and percentage change in step length and step width was considered between the gate open and gate close condition and the four steps leading up to and crossing/stepping around the gate (cross-3, cross-2, cross-1, cross) using a 2 x 4 way ANOVA. Finally, the step adjustments of the gate close condition were considered separately in order to allow us to detail exactly how an obstacle is circumvented. This was done using the categories of foot adjustment detailed above and the percentage of trials each strategy was used is given. For all statistical analyses Greenhouse-Geisser was reported when the assumption of sphericity was violated. Significant main effects were followed up with post-hoc tests using a Bonferroni correction to adjust for multiple comparisons and significant interactions were followed up with a Pillai's Trace simple main effects test. Partial eta-squared is reported as a measure of effect size and the significance level set at 0.05.

3. Results

Participants successfully completed all conditions without collision. In the gate close trials all participants circumvented the obstacle rather than stepping over it.

3.1. Anticipation of an obstacle appearance

3.1.1 Trunk movement measures

No significant effects of condition were found for any of the measures ($p>.05$). A significant main effect of phase was found for medio-lateral velocity [$F(1,14)=4.90$ $p=.044$ $\eta^2=.26$], anterior-posterior velocity [$F(1,14)=34.75$ $p<.001$ $\eta^2=.71$] and medio-lateral acceleration [$F(1,14)=6.49$ $p=.023$ $\eta^2=.32$]. In each case velocity and acceleration was greater in the before phase compared to the after phase. Significant interactions between condition and phase were found for anterior-posterior velocity and acceleration [velocity: $F(2,28)=13.12$ $p<.001$ $\eta^2=.48$, acceleration: $F(2,28)=5.22$ $p=.012$ $\eta^2=.27$] and medio-lateral acceleration [$F(2,28)=5.25$ $p=.012$ $\eta^2=.27$]. For anterior-posterior velocity and acceleration simple main effects tests found no effect of condition in the before phase. However, in the after phase an effect of condition was found [velocity: $F(2,13)=8.41$ $p=.005$ $\eta^2=.56$, acceleration: $F(2,13)=12.47$ $p=.001$ $\eta^2=.66$]. In both cases no difference was seen between no gate and gate open condition but a difference was seen between these and the gate close condition. A higher velocity and smaller acceleration was seen in the former (velocity: no gate = gate open > gate close, acceleration no gate = gate open < gate close). In contrast, for medio-lateral acceleration a main effect of condition was found for the before phase [$F(2,13)=8.44$ $p=.004$ $\eta^2=.57$] and not the after phase, this effect was due to a smaller acceleration in the no gate condition compared to the gate open and gate close condition (no gate < gate open = gate close). Data can be found in Table 1.

INSERT TABLE ONE HERE

3.1.2. Spatial parameters of foot placement

No significant effects of condition were found for any of the measures ($p>.05$). For step length and step width a significant main effect of phase was found, with steps shortening and widening in the after phase compared to the before phase [step length: $F(1,14)=14.85$ $p=.002$ $\eta^2=.52$ and step width: $F(1,14)=29.85$ $p<.001$ $\eta^2=.68$]. In addition an interaction between condition and phase was found for both measures [step length: $F(2,28)=16.88$ $p<.001$ $\eta^2=.55$ and step width: $F(2,28)=8.26$ $p=.002$ $\eta^2=.37$]. Simple main effects tests of condition for each phase indicated that for step length there was no significant effect of condition in the before phase ($p>.05$). However, there was a significant main effect of condition in the after phase [$F(2,13)=8.014$ $p=.005$ $\eta^2=.55$] this was due to a longer step length in the no gate and gate open condition compared to the gate close condition. In contrast, for step width there was a significant effect of condition in the before phase [$F(2,13)=6.97$ $p=.009$ $\eta^2=.52$], due to an increased step width in the no gate condition compared to the gate open or gate close condition. However, there was no significant effect of condition in the after phase ($p>.05$). Data can be found in Table 2.

INSERT TABLE TWO HERE

3.2. Circumvention of an obstacle

3.2.1. Number of step length and step width adjustments

For the number of adjustments to step length and step width, a significant main effect of condition [length: $F(1,14)=20.66$ $p<.001$ $\eta^2=.60$, width: $F(1,14)=329.25$ $p<.001$ $\eta^2=.96$] and step number was found [length: $F(3,42)=3.40$ $p=.026$ $\eta^2=.20$, width: $F(3,42)=17.83$ $p<.001$ $\eta^2=.56$]. These effects were due to a greater number of adjustments in the gate close compared to the gate open condition and a greater number of adjustments in the cross and cross-1 step compared to the cross-2 or cross-3 step. A significant interaction between condition and step number was also found for step width [$F(3,42)=21.52$ $p<.001$ $\eta^2=.61$], when broken down using simple main effects tests there was no significant effect of step number for the gate open condition demonstrating that the number of adjustments did not differ across the steps when the gate remained open. In contrast, an effect of step number was found for the gate close condition [$F(3,12)=41.78$ $p<.001$ $\eta^2=.91$], with a greater number of adjustments in the cross and cross-1 step compared to the cross-2 or cross-3 step (cross=cross-1 > cross-2=cross-3). No significant interaction between condition and step number was found for step length ($p>.05$). These data can be found in Figure 2.

INSERT FIGURE 2 HERE

3.2.2. Percentage change in step length and step width

Secondly the absolute percentage change in step length and step width adjustments were considered. For both step length and step width a significant main effect of condition [length: $F(1,14)=26.14$ $p<.001$ $\eta^2=.65$, width: $F(1,14)=172.95$ $p<.001$ $\eta^2=.93$] and step number was found [length: $F(3,42)=5.63$ $p=.002$ $\eta^2=.29$, width: $F(3,42)=13.88$ $p<.001$ $\eta^2=.49$]. These effects were due to a greater percentage change in the gate close compared to the gate open condition and a greater percentage change in the cross and cross-1 step compared to the cross-2 or cross-3 step. A significant interaction between condition and step was also found for step width [$F(3,42)=17.06$ $p<.001$ $\eta^2=.55$], when broken down using simple main effects tests there was no significant effect of step for the gate open condition demonstrating that the percentage change in step width did not differ across the steps when the gate remained open. In contrast, a significant effect of step number was found for the gate close condition [$F(3,12)=22.87$ $p<.001$ $\eta^2=.85$], with a greater percentage change in the cross step compared to the other steps and then a greater percentage in the cross-1 step compared to the cross-2 or cross-3 step (cross > cross-1 > cross-2=cross-3). No significant interaction between condition and step was found for step length. These data can be found in Figure 2.

3.2.3. Categorisation of foot placement adjustments

Finally the type of foot placement was considered. Figure 3 shows the relative percentage of trials each strategy was used across each of the four steps. From this we can see that participants predominately used short adjustments on cross-3 and then predominately changes in step width which took them away from the obstacle on cross-2, cross-1 and cross. In addition to 'away' adjustments participants also used short away adjustments on cross-2, cross-1 and cross. Very few adjustments were long adjustments, in fact only 2.5% of adjustments included a lengthening of the step, whereas 43% of steps were adjusted by shortening (combination of short, short away and short towards). A few adjustments were towards the obstacle (across all steps this was 7%) but as stated above the majority took participants away (across all steps this was 77%). Figure 4, breaks down the strategies chosen by participant, the highlighted sections show the most commonly used strategy. From this it is clear that some participants favoured a single type of adjustment, with 8 participants favouring away adjustments, 1 participant favouring short away adjustments and 1 participant favouring short adjustments. The remaining 5 participants equally favoured short, short away and away adjustments.

INSERT FIGURE 3 HERE
INSERT FIGURE 4 HERE

4. Discussion

The two main aims of this study were: 1. To determine how adults anticipate the possibility of an obstacle appearing in their pathway and 2. To determine how adults circumvent an obstacle when it does appear. We discuss our findings in relation to each of these two aims in turn. Firstly, in terms of anticipation, we compared the way in which adults walk when there is the *possibility* of an obstacle (gate close and gate open trials) compared to *no possibility* of an obstacle (no gate trials). For movement prior to the obstacle trigger, we found that medio-lateral trunk acceleration is increased and step width is decreased for trials where there is the possibility of an obstacle appearing compared to trials with no possibility. In essence this demonstrates that the healthy adults are anticipating that an obstacle may appear and are adjusting their motor control. Previous research considering anticipation has primarily focused on anticipation of a trip or fall (Pijnappels et al., 2001; Potocanac et al., 2014; Pater et al. 2015). Our findings are in line with these previous studies, which also demonstrated a degree of anticipation when warned that a perturbation could be introduced. Interestingly, Pijnappels et al. (2001) concluded that although their participants did adjust their walking pattern in an anticipatory manner that these adjustments would not have helped to prevent a fall or indeed help with recovery. Ours is the first study to demonstrate anticipation of this type in a low harm obstacle avoidance setting.

Previous research has shown that narrow steps are related to a decrease in medio-lateral stability (McAndrew Young and Dingwell, 2012) and so the changes in these two variables (ML acceleration and step width) are likely to be related. Comparing the finding of the current study with those which have previously considered anticipation, we see that Pijnappels et al. (2001) saw a significant widening of step width during anticipatory trials, while we see a significant narrowing of step width. The reason for these differing results is most likely due to the task used, in Pijnappels et al.'s (2001) study participants were anticipating a trip, widening step width increasing the base of support and therefore reducing balance demands. In the current study, we were considering obstacle circumvention and so by decreasing step width the participants may have been attempting to maintain foot positions as close to the centre of the path as possible in order to allow for fast adjustments in either direction if one of the gates were to close.

Regarding the second aim of the study, to detail how participants circumvent an obstacle, we have demonstrated that a greater number of step adjustments are made as the participants gets close to the obstacle, with fewer adjustments made to cross-3 and cross-2 compared to cross-1 and the crossing step. We have also demonstrated that the degree of change in step length and step width increases as the participant approaches the gate, i.e. the degree of change is greater for the crossing step compared to cross-1 which in turn is greater than cross-2. Given that for the crossing step and the one preceding it this is not simply a function of the number of adjustments this would suggest that adjustments are made as often during these steps but that those made in the crossing step are larger changes compared to those made in the step preceding this. This supports previous research focusing on circumvention which demonstrates that for this task adjustments are made not just to the 1-2 steps prior to crossing an obstacle but also 1-2 steps prior to that (Vallis and McFadyen, 2003). In the current study relatively few adjustments were made at cross-3 (three steps preceding the crossing step), however, at this point the gate would only just have closed. A direct comparison of the number of adjustments steps between this study and the Vallis and McFadyen (2003) study which also considered circumvention cannot be made as this previous study did not categorise adjustment steps in the same way. Together these findings demonstrate an earlier adjustment to movement which is then further adjusted to meet the demands of the task, this is in line with studies that have considered the avoidance of moving obstacles (Cinelli, Patla, & Allard, 2008; Gerin-Lajoie, Richards, & Mcfadyen, 2005).

In the current study we categorised step adjustments as being long, short, towards the obstacle, away from the obstacle etc. The categorisation of step adjustments indicated that the majority of participants chose a short adjustment three steps preceding the crossing step and then adjustments to step width which took the participant away from the obstacle. Unsurprisingly, there were very few instances of participants making adjustments to step width which took them towards the gate, however, more surprisingly is that only two participants showed any instances of step lengthening adjustments (and these participants only did this for a single step on one trial). Previous research has shown that step lengthening is the preferred adjustment to step length when stepping over, with this the preferred strategy in healthy adults (Moraes et al.,2007), older females (Weerdesteyn et al. 2005) and individuals recovering from stroke (Den Otter, Geurts, de Haart, Mulder, & Duysens, 2005). In fact Chen and colleagues found that short step strategies were only adopted when response time was short, in all other cases a long-step strategy was favoured (Chen et al. 1994). Furthermore, Moraes (2014) argues that step lengthening provides more time to alter limb trajectory and allows for maintenance of forward progression which may account for this preference. In the current study we found the opposite, that participants favoured shortening of steps. This is not due to time constraints as participants essentially had four steps to make the adjustment. Therefore, it would seem that the reason for this difference is due to the task. The studies described above have all considered a stepping over action which requires very different postural adjustments. The key here may be the necessity in circumvention for an adjustment to step width, which is not necessary when stepping over. In order to walk around an object, increasing step width allows you to deviate from your path. However, as step width increases we typically see a decrease in step length in order to ensure a stable base of support (for example see Bierbaum, Peper, Karamanidis & Arampatzis, 2010). Supporting this, Vallis and McFadyen (2003) found a tendency to decrease or shorten step length as step width was increased when adults were circumventing an obstacle. Patla et al. (1999) suggested some criteria for the selection of foot placement adaptation, these were efficiency, stability and maintenance of forward progression. Although increasing step length maintains forward progression (Moraes 2014) and this has been shown to be the dominant strategy in stepping over tasks, it would seem that in this task the key factor is one of stability, hence the shortening of step length.

In many previous studies which have considered adjustments to an unexpected obstacle participants have only been given one step to make necessary adjustments and so that one step is an adjustment step. In the current study, we did this slightly differently, in essence we gave participants at least four steps to adjust to the obstacle, they could have chosen to adjust their walking path very early, i.e. four steps away and then not made another adjustment, equally they could have adjusted very late. Therefore, when we categorised step adjustments we only included those steps where there was a significant change to step length or step width. This slightly different analysis was required given the difference in method, but it does mean that the participant may have made small adjustments to say step width which over three steps took them away from the obstacle but that these were not classified as step adjustments. This is how in very few cases participants were able to circumvent an obstacle without seeming to make any adjustments to step width.

One limitation to this study is that we could not control the exact situation under which the gate closed, for example, sometimes the right gate will have closed when the right foot is the lead foot and sometimes when the left leg is the lead foot. In essence this means that on some trials the circumvention needed a smaller adjustment compared to other trials. In this study this was necessary to ensure unpredictability of whether the gate would close and indeed which gate would close. However, future studies could examine this in more detail.

In conclusion, we have shown that the way in which healthy adults walk is different when there is the *possibility* of an object appearing in their pathway even when the risk of harm is low. We have also demonstrated that adults can efficiently circumvent an obstacle which appears unpredictably and that they do this by favouring a shortening and widening of step placement which seemingly maintains stability while deviating from the original path. This study provides a description of object circumvention in healthy adults against which circumvention in other populations can be considered.

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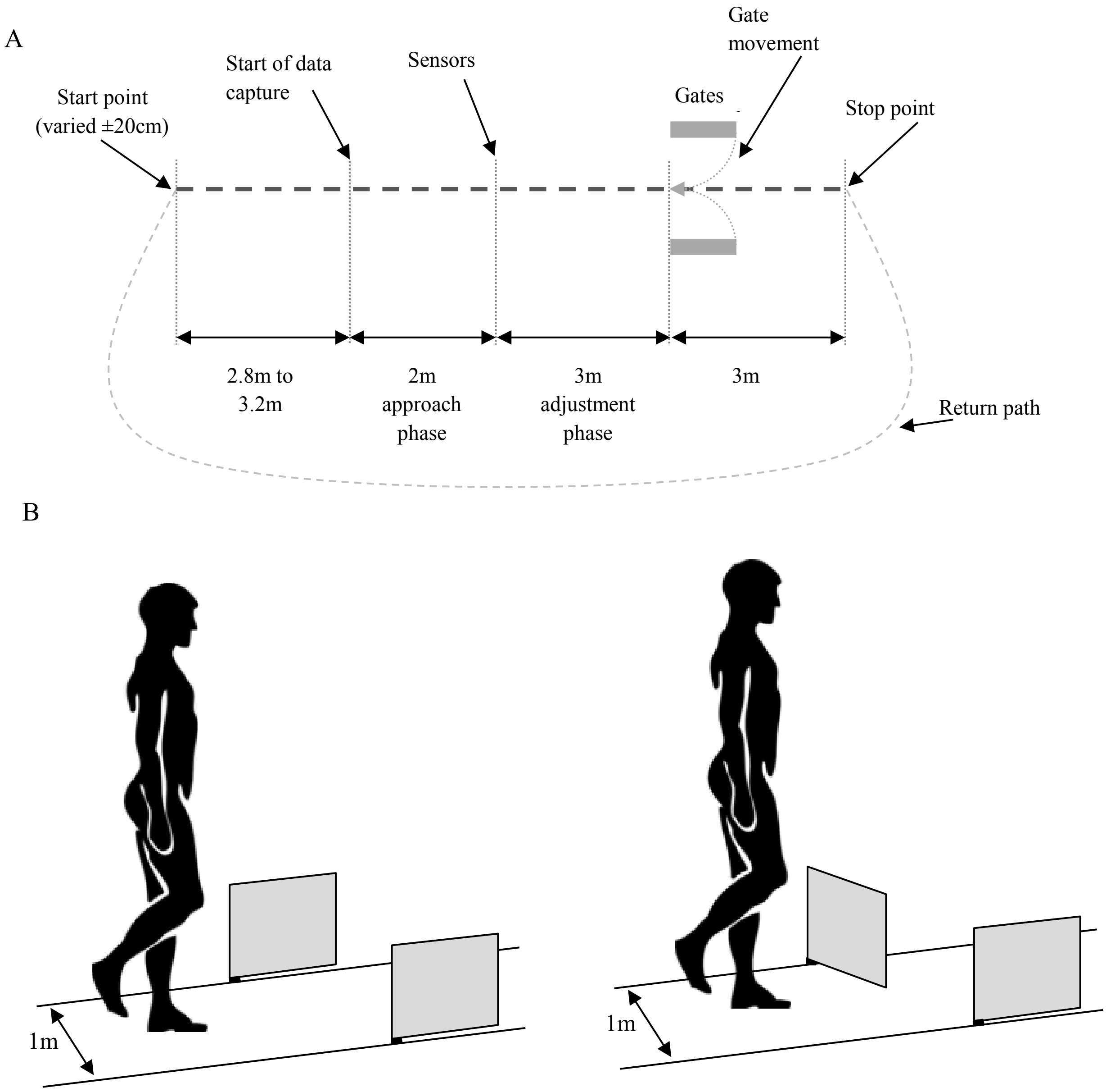

Figure 1. A. bird's eye view of the set up including the walking path, the return path and the location of the sensors and gates. B. Left - a gate open trial, right and gate close trial.

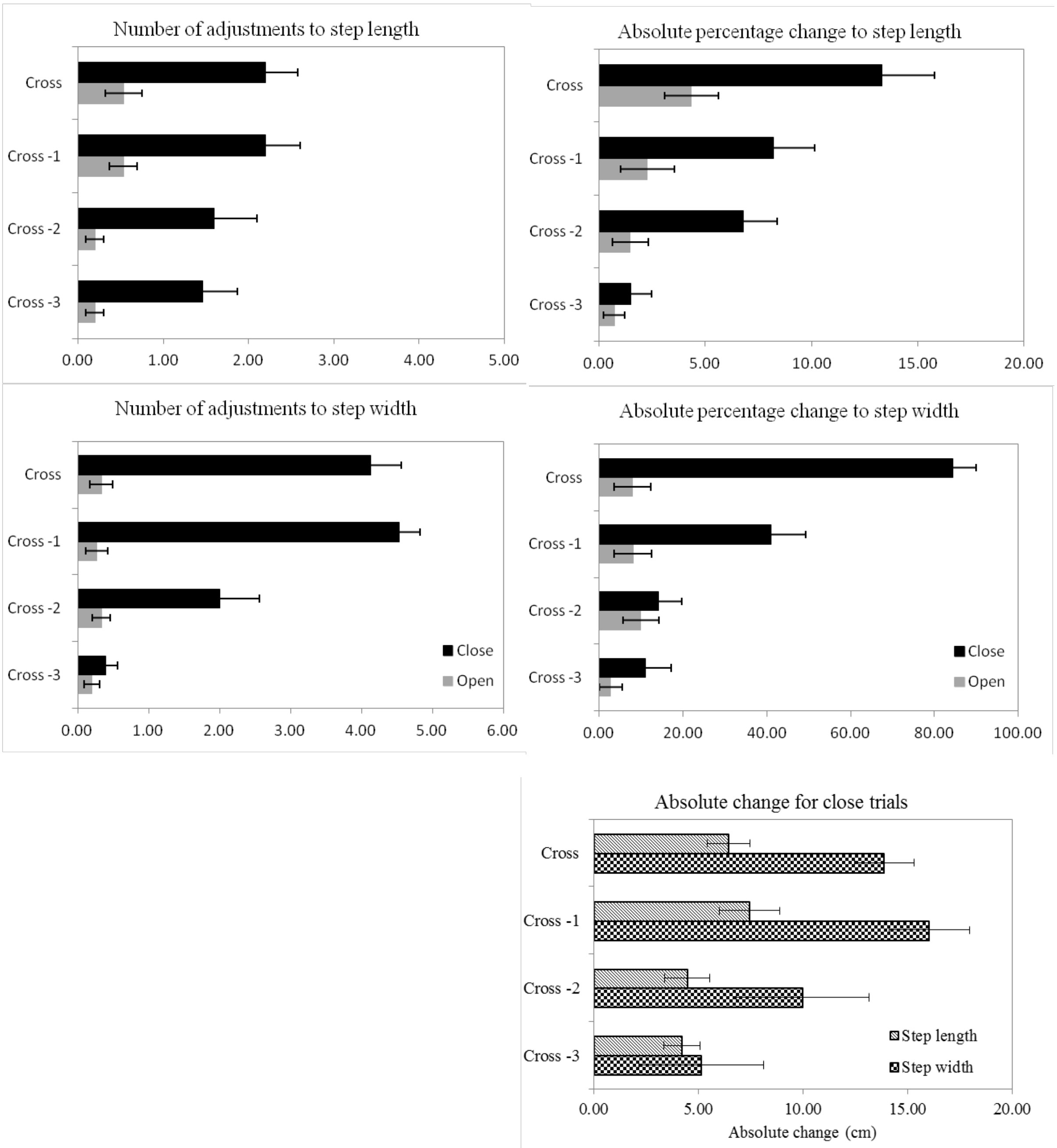

Figure 2. Number of adjustments to step length and step width on the left and percentage change to step length and step on the right. Adjustments are shown for both gate open and gate close conditions and for the crossing step and the three steps preceding this. In addition the absolute change for close trials only is given for reference. Error bars are standard error.

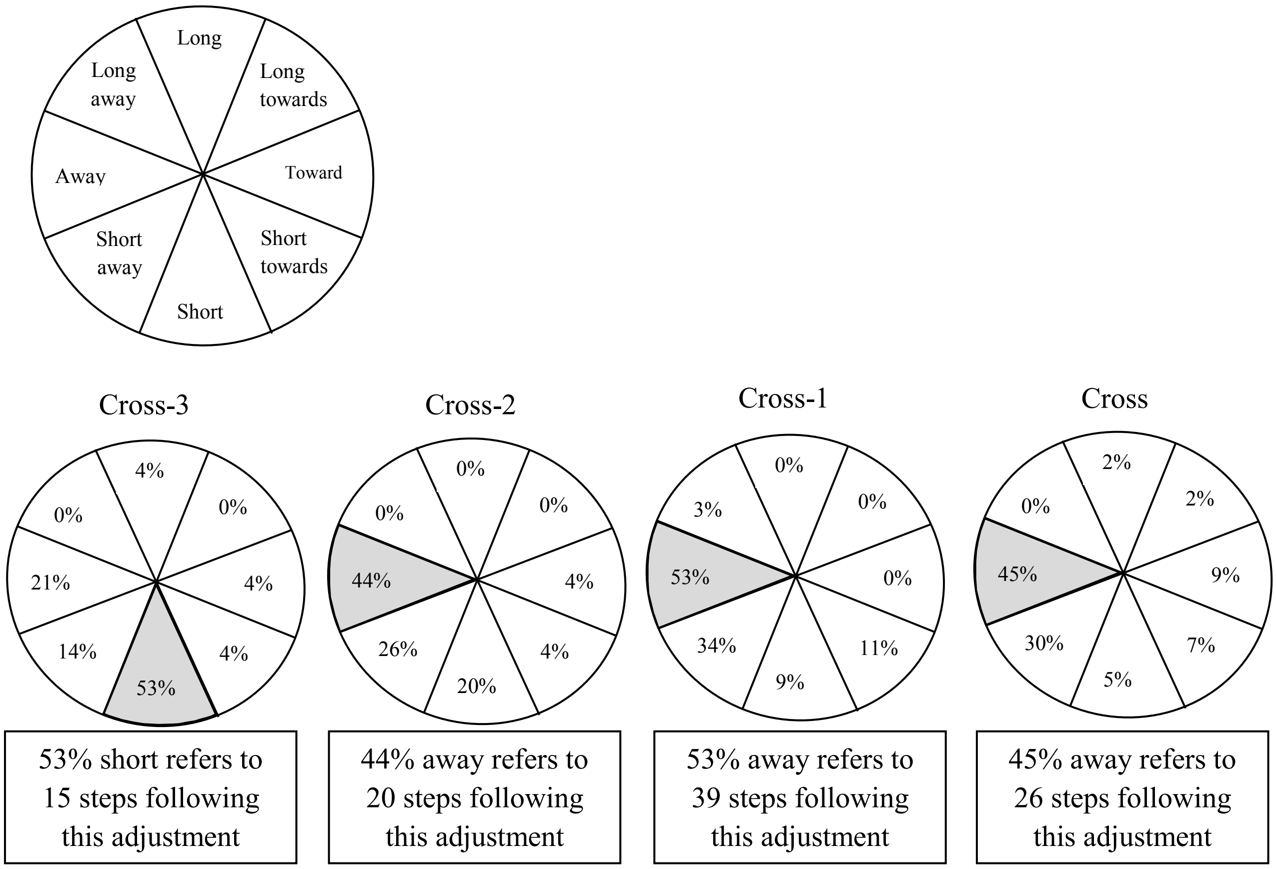

Figure 3. An illustration of the strategies chosen for adjustment steps. Given that the away and towards movements were in different directions depending on the foot in motion and the position of the obstacle a standard direction is used for the purposes of this illustration (see top left), thus a movement away from the obstacle (regardless of whether it was actually a movement to the left or to the right) is depicted in the left segment. As these depictions include adjustment steps only the pool of steps is different for cross-3,-2,-1 and cross. Therefore, the number of actual steps that the dominant strategy refers to is given. The most commonly used strategy at each step is highlighted.

Obstacle circumvention

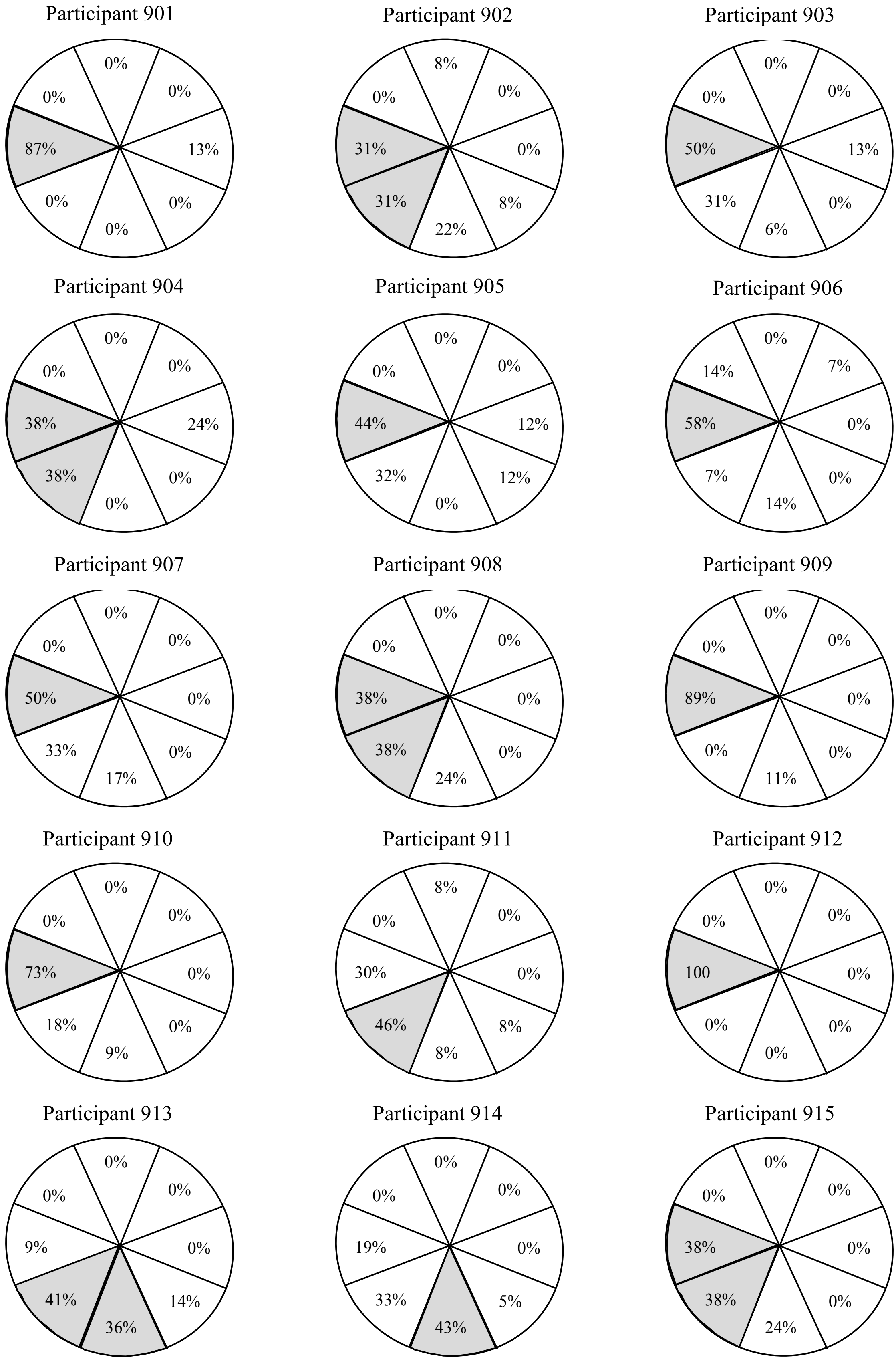

Figure 4. An illustration of the percentage of times the different strategies were chosen depicted for each participant. Each segment of the circle represents a different movement strategy, see Figure 3 for the standard template.

Table 1. Trunk velocity and trunk acceleration for all conditions (no gate, gate open, gate close) and both phases (before obstacle trigger and after obstacle trigger). Standard deviation is given in brackets. Final column summarises the significant main effects and interactions.

		No gate		Gate open		Gate close		sig
		Before	After	Before	After	Before	After	
Velocity (ms^{-1})	ML	0.110 (0.32)	0.112 (0.34)	0.119 (0.30)	0.108 (0.32)	0.121 (0.30)	0.114 (0.34)	Phase
	AP	1.39 (1.42)	1.38 (1.35)	1.40 (1.47)	1.40 (1.62)	1.40 (1.54)	1.33 (1.20)	Phase Condition x phase
	V	0.191 (0.42)	0.190 (0.40)	0.183 (0.37)	0.178 (0.43)	0.182 (0.39)	0.179 (0.43)	
Acceleration (ms^{-2})	ML	1.51 (0.46)	1.53 (0.48)	1.68 (0.39)	1.55 (0.46)	1.70 (0.38)	1.52 (0.49)	Phase Condition x phase
	AP	1.58 (0.32)	1.53 (0.18)	1.63 (0.09)	1.68 (0.13)	1.62 (0.11)	1.71 (0.15)	Condition x phase
	V	2.49 (0.57)	2.48 (0.54)	2.45 (0.44)	2.36 (0.45)	2.44 (0.47)	2.40 (0.47)	

Table 2. Spatial parameters of foot placement: step length and step width for all conditions (no gate, gate open, gate close) and both phases (before obstacle trigger and after obstacle trigger). Standard deviation is given in brackets. Final column summarises the significant main effects and interactions.

	No gate		Gate open		Gate close		sig
	Before	After	Before	After	Before	After	
Step length	55.57	55.15	54.71	54.86	54.65	52.64	Phase
(cm)	(5.9)	(5.8)	(5.5)	(5.8)	(5.8)	(56.1)	Phase x condition
Step width	17.56	17.53	16.33	17.13	16.49	18.33	Phase
(cm)	(1.9)	(2.1)	(2.2)	(2.3)	(2.5)	(2.3)	Phase x condition