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ALTERNATE FOOT PLACEMENT: INVESTIGATING THE ROLE OF GAIT PARAMETERS, PLANAR OBSTACLE COMPLEXITY, AND ATHLETIC TRAINING

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ALTERNATE FOOT PLACEMENT: INVESTIGATING THE ROLE OF GAIT PARAMETERS, PLANAR OBSTACLE COMPLEXITY, AND ATHLETIC TRAINING

by

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Abstract

On a daily basis modifications, based upon environmental demands and the capabilities of the individual, are made to the locomotor pattern to enable avoidance of undesirable landing areas (i.e. planar obstacles). Athletes and dancers have been suggested to have superior perception-action coupling compared to non-athletes, allowing them to perform various tasks at a greater speed without a loss of precision (Federici et al., 2005; Gerin-Lajoie et al. (2007). The current study assessed non-athletes, dancers, and field athletes to investigate whether training influences the maintenance of forward progression and stability in relation to alternate foot placement during planar obstacle avoidance. Eleven field athletes (22± 2.68 years) having recent/current sport participation, 10 individuals (21.1± 1.1 years) with previous/current dance training, and 12 non-athletes (21.75± 1.54 years) with no participation in organized sport in >5 years were asked to walk to a goal (~13 m away) at a self-selected pace, avoiding any obstacle(s) when present (50% of trials; 15cm wide x 70cm long rectangles, projected ~8m from the start position). Obstacle conditions were: 1) Single obstacle appearance (SIN) where the obstacle (at N) appeared when the participant was 2 steps away from the first obstacle (N-2) ; 2) Double obstacle appearance was delayed (DDEL) until at N-2; and 3) Double obstacle appearance after participants reached steady state (i.e. ~3 steps from start)(DSS). All participants, regardless of training, stepped medially during SIN. Avoidance during double obstacle conditions was variable (i.e. medial-medial, medial-lateral, and lateral-medial). The variability of behaviour, computed as a coefficient of unalikeability (the proportion of possible comparisons which are unalike), had significant moderate positive correlations with the minimum Dynamic Stability Margin at N-1 for DSS and DDEL (r = 0.36; r = 0.44, respectively, *p*<0.001) and a significant weak positive

relationship with ML COM variability (r = 0.28, $p<0.05$) during DDEL. To a degree, greater ML COM variability leads to avoidance behaviour that exploits forward progression more so than stability, as stepping medially perturbs the COM the least from its forward momentum but narrows the BOS creating instability that must be offset in the following step. Avoidance of planar obstacles at a comfortable walk lacked context specificity to dance or field sport training to elicit any behavioural differences.

Table of Contents

Introduction

Visual Control of Locomotion

Vision is often argued as the most important source of sensory input for the planning and execution of obstacle avoidance behaviour. In 1958, Gibson reasoned for vision to be considered as a kinaesthetic modality.

> *"An eye is a device which registers the flow pattern of an optic array as well as the static pattern of an array. ... This mode of optical stimulation is an invariable accompaniment of locomotor behaviour and it therefore provides 'feedback' stimulation for the control and guidance of locomotor behaviour." (p.185)*

Vision is the primary source of sensory information that allows locomotion to be tempered in a proactive feedforward manner by providing knowledge about the environment at a distance, particulars of self-motion, and the position of the body (and its segments) in relation to the surroundings (Patla, 1998). A pioneering study in regards to the control of locomotion through visual feedback investigated the approach of long jumpers to the take-off board (Lee, Lishman, & Thomson, 1982). The approach for long jumping was commonly instructed by coaches to be done in a stereotyped manner and the task requires precise step regulation while running at high speeds. In an attempt to improve their athletes' consistency, coaches in the former Soviet Union created audio feedback from seismographic recordings of the run-up (Monastyrev, Nepopalov, & Pustokhin, 1982). While coaches and athletes believed that vision influenced their take-off very little, the investigation by Lee et al. (1982) discredited this assumption and indicated that visual control was used to regulate gait for precision in foot placement during take-off.

Lee et al. (1982) used cinematographic techniques to record and analyze the approach of three experience female long jumpers. Hay (1988); Berg, Wade, and Greer (1994) built upon the work of Lee and colleagues (1982) by investigating larger samples of long jumpers; the cohorts encompassed both genders and a wider range in age and jumping experience/expertise. Hay (1988) investigated the performance of expert male and female long jumper during competition, where Berg et al. (1994) used a sample of 15 male high school athletes. The step variability pattern during the approach to the take-off board consisted of two distinct phases: 1) an accumulation of variability in the foot placement relative to the take-off board during the initial stage of the approach; 2) followed by a steep reduction in the variability of foot placement as the athlete's proximity reaches about three steps from the take off board. This pattern of step variability over the course of the approach, as depicted in Figure 1 below, remained consistent irrespective of the magnitude of standard deviation in toe to board distance.

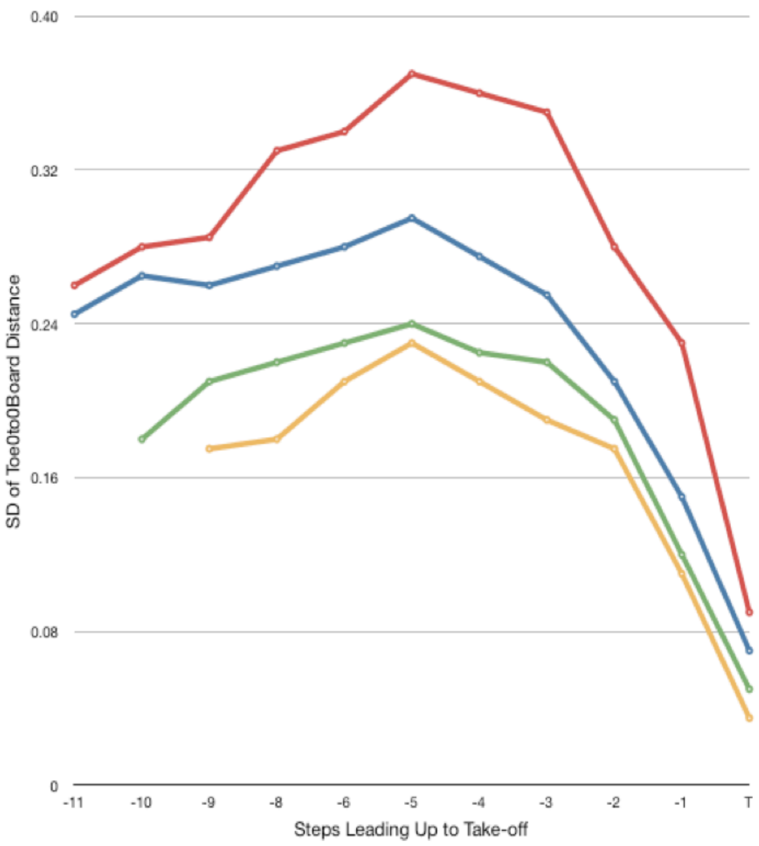

Figure 1. Mean standard deviation (SD) of the toe-to-board distance, defined as the distance between the toe of the support foot to the front edge of the take-off board, for the take-off step (T) and the preceding 11 steps. Red represents the three females of the Lee et al. (1982) work. Green and yellow represent the expert male and female long jumpers respectively, from the Hay (1988) study. The novice males in the Berg et al. (1994) study are blue. Adapted from Berg et al. (1994).

It was suggested that the first phase is a product of the practiced stereotyped run up that the athletes were coached to perform, where any deviation in one foot placement would be compounded and carried-over to the subsequent steps, as no step length adjustment would be made to account for the inaccuracy (Hay, 1988; Berg et al., 1994). The precipitous reduction in step variability that followed was attributed to the implementation of visual input to control locomotion. The distance at which the long jumpers begin to use vision to govern their step length is inconsistent among these studies; Hay (1988) reported this decrease at around five steps before take-off, where

Berg et al. (1994) estimate closer to four. However, the criterion used by the authors to identify this change was not the same and likely contributes to the differences in the findings. Regardless of the discrepancy in this ‘turning point’, both studies found the majority of the step length adjustment (62.4%) made by the athletes occurred during the final two steps.

The rate of incoming visual information, in the form of retinal expansion termed the optical variable Tau, is used to infer the temporal distance when approaching an obstacle at which contact will occur (i.e. Time-to-Contact (TTC))(Lee, 1980). The size of the objects’ image projected onto the retina is inversely related to how far away the individual is, where the closer the obstacle becomes the larger the retinal image becomes at a proportional speed. A study by Warren, Young, and Lee (1986) corroborated this notion of visual perception being coupled with action by examining within step length adjustments during running by tying retinal input of the foot placement area to the modulation of vertical impulse (a component of gait modulation).

Gaze fixations upon objects that pose potential threats to movement progression may be used to calculate TTC and thus, a substantial amount of literature has measured and quantified gaze behaviours of individuals as they locomote through a variety of environments and perform various tasks; it is assumed that where one is looking is where attention is being allocated (Tresilian, 1999; Findley & Gilchrist, 2004). Gaze behaviour is often characterized into: 1) objects fixated, which indicates the objects of interests within an environment; 2) the number of fixations, the frequency in which information about the environment needs to be updated; and 3) fixation duration, which is regarded as the time it takes to process visual information.

During unobstructed walking Patla and Vickers (2003) have shown that individuals spend the majority of their time in “travel gaze fixation” where the eyes are stabilized in their fixation about 2 m ahead and passively carried along as the individual moves through space. The salient information from the environment is obtained in a spatio-temporal manner, generalizable to no more than three steps ahead for precise foot placement, as substantiated in numerous studies examining obstacle avoidance and footfall targeting (e.g. take-off board or stone stepping) (Cinelli, Patla, & Allard, 2009; Lee et al., 1982; Patla & Vickers, 1997; Patla & Vickers, 2003). When approaching an obstacle, Patla and Vickers (1997) demonstrated, that an obstacle is fixated upon at one to two steps before crossing the obstacle (increase of frequency and duration) and while stepping over an obstacle the landing area is fixated. This preference to fixate two steps ahead appeared to hold true when individuals had to modulate their gait to target their foot placement to step on targets along a path (spaced to average step length and width or irregularly spaced)(Patla & Vickers, 2003). Patla and Vickers (2003) required participants to target 17 footprints along a 10 m path and partitioned the gaze behaviour into footprint fixations and travel fixation. Travel gaze was dominant for the duration of the trial and was interspersed with target landing fixations (occurring on average two steps in advance).

While gaze behaviour has been well characterized during the navigation of multiple footholds along a path (Hollands & Marple-Horvat et al., 1995; Hollands &

Marple-Horvat, 1996, 2001; Patla & Vickers, 1997; Crowdy et al., 2000; Patla & Vickers, 2003) this same understanding has not been extended to the avoidance of multiple ground level obstacles. Marigold and Patla (2007) used a complex terrain with varying surface types in order to determine whether it the undesirable landing spots or the chosen footholds the are fixated, and when these are fixated as an individual navigates through the environment. The experimental setup was composed of an uncluttered approach area (~2.7 m), multi-surface area (~2.5 m), and an uncluttered exit to a goal (~2.3m). The multi surface had 6 types of terrain: 1) two sections of solid level, 2) three tilted sections, 3) three sections of compliant medium-density, 4) three tightly packed gravel sections, 5) three sections with irregularly spaced rocks, and 6) one slippery section of white ultra-high molecular weight polyethylene. When traversing this enriched environment a disappearance in the use of travel gaze fixation was found (i.e. <1% of fixations were classified as such) and the eyes were found to actively search the environment and fixate on areas that they would eventually step onto. It was also found that individuals often fixated upon transition areas between two areas of two different surface qualities and it was suggested by Marigold and Patla (2007) that this would allow for information about both surfaces to be attended to while optimizing the amount of time to be spent upon surfaces that were selected for foot placement. The temporal relation between the stepping behaviour and gaze revealed fixation of the row of sections two steps ahead for the majority of the time spent traversing to the goal.

In addition to the literature on gaze fixation and duration during obstacle avoidance, there has been recent investigation as to how footholds while crossing complex terrain are affected when the window of visibility about the individual is manipulated. Similar to the aforementioned study by Marigold and Patla (2007), the research by Matthis and Fajen (2013a; 2013b) focussed on extending the literature on obstacle avoidance to included environments of greater complexity as preceding research tends to focus paradigms containing a single obstacle (Krell & Patla, 2002; Patla, Prentice, Robinson, & Neufeld, 1991; Patla et al., 1999; Moraes, Allard, & Patla, 2007; Moraes, Lewis, & Patla, 2004; Moraes & Patla, 2006). The ability to navigate a cluttered terrain of multiple planar obstacles (measured by the number of collision with the obstacles, 15 x 15 cm blue squares) from a start to a goal position 3.6 m away.

The amount of visual information was manipulated by either projecting the obstacles strewn across the entire path or co-ordinate the window in which the obstacles were visible with the head movement of the individual as the progress to the goal. The visibility windows had 5 possible radii, increasing incrementally by step length from 1 to 5 (step length calculated as 70% of the individuals leg length). The number of the collision and the normalized speed at which the participant traverse the terrain to the goal were the were the dependent measures, with the emphasis placed upon the number of collisions.

The visibility window of one step had a significantly higher incidence of collisions compared to all of the other window sizes and the full vision condition. While a visibility window of two step did not differ in collisions from those that were larger; individual selected to walk at a significantly slower pace when only given two steps of information, similar to the more narrow window of one step. A subsequent study was performed that had visibility windows ranging from a single step to three steps worth at increments of half a step. Where again there was no significant difference between a window revealing three steps worth of visual information and being presented with full vision of the obstructed path. The number of collision was highest during the 1 step visibility window and then significantly drops for each incremental increase in the size of the window, with the most precipitous drop occurring between 1 and 1.5 step lengths of visibility. The tendency for individuals to slow their gait when given a window smaller than two steps was observed once again. Based upon these findings it was suggested by Matthis and Fajen (2013b) that while it is possible to successfully avoid a single obstacle while a step or less of visual information (Patla et al., 1991; Patla et al., 1999; Reynolds & Day, 2005), when the terrain increases in complexity 2-3 steps of preceding visual information is required. Visual information extending beyond that may be useful in route planning to a distance obstacle but is not imperative to avoid undesirable landing areas.

This apparent feedforward coupling of vision and action is a fragment of the continuous causal relationship between the individual and the environment proposed by Warren (2006), where the individual perceives and acts upon the environment. When the individual performs an action, the state of the environment changes, through information provided by spatio-temporal changes in the optic array, which in turn is used to modulate how the individual further acts upon (ex. change in vertical impulse) the environment, which then starts the cycle over (Gibson, 1966; Lee, 1976; Warren, Young, & Lee, 1986). The gait cycle is highly efficient at harnessing and redirecting passive mechanical forces; during single support a walker is mechanically similar to an inverted pendulum, where the ankle constitutes the pivot point that a large COM travels about (Cavagna & Margaria, 1966; Winter, 1995). As the COM falls forward at the end of single support the contralateral (leading) leg strikes the ground ahead performing negative work to oppose this downward “falling” motion, simultaneously the trailing leg provides positive work (i.e. propelling the COM in the forward direction). Conjunctively these forces redirect the COM into an upward trajectory beginning the next step where the COM passes over the ankle in a prescribed arc of an inverted pendulum. An ideal inverted pendulum without friction or resistance is perfectly energetically efficient. While human bipedal gait is efficient the major determinant of the metabolic cost of walking is thought to be the rate work required (for a given step frequency) increasing with the fourth power of step length to restore the energy lost during the step-to-step transition (Kuo & Donelan, 2010).

Matthis and Fajen (2013a) used the inverted pendulum model to investigate if the same efficiency of gait over flat obstacle free terrain is maintained over a complex terrain and if the amount of preceding visual information of this cluttered terrain given affects the incidence of obstacle collision and how closely the resulting gait pattern adheres to the optimal pendular arc. The same set up as the first experiment by Matthis and Fajen (2013b) described earlier with the half step increments for the visibility widows ranging from one to five steps worth was performed with an added time constraint of 6 s to reach the goal (average walking speed of 0.6 m/s). A passively moving 3D inverted pendulum (modeled from the influence of gravity with the initial position and velocity of the subjects COM at the beginning of the step) was compared to how the subject moved to the goal in actuality. Energy recovery was the second measure, the amount of work done to increase the potential energy of the COM that is recovered in the for of kinetic energy, conveying the efficiency of each given stride.

Energy recovery was found to be significantly lower in the 1 and 1.5 step window size conditions ($p<0.01$) and slightly lower at 2 steps ($p= 0.047$). These conditions also exhibited significantly slower speed of walking, which is inextricable from energy recovery and thus clouds the degree of precision to which the loss of energy efficiency was calculated. The finding, regardless of speed, that the recovery of mechanical energy is lower when the window is smaller the two steps worth is of note. The importance of this given size of visibility is mirrored by the matching (i.e. no significant difference) of the model and subject's actual COM trajectory when the visibility window encompassed two or more lengths ahead. Matthis and Fajen (2013a) suggest that when visibility is constrained to 1.5 step lengths it is more difficulty to modulate the passive trajectory of the COM as only the initial velocity of the COM can be affected; given a greater window then the location of the lead foot may also be modulated to improve the walking performance.

Throughout the literature discussed, as to visual control of locomotion, one theme tends to resound; that of the role of vision in a feedforward manner that samples highly from the preceding two steps worth of information to effectively and efficiently avoid various obstacles and gain stable footholds. When undesirable landing areas (e.g., pothole, path of ice, a puddle, etc.) present along the travel path common modifications to locomotion emerge. Individuals may adjust step length or width, alter the speed at which they are moving, and/or circumvent the area by changing direction. Environmental demands and abilities of the individual influence which adjustment or combinations of adjustments are employed.

Alternate Foot Placement

When the success of locomotion is changed from the ability to target footholds to the execution of finding an alternate foot placement due to an undesirable landing area (i.e., avoidance behaviour about a planar obstacle), the degrees of freedom in available footholds is increased and the locomotor adjustments are proposed to be determined by a set of internal rules in addition to visual control (Patla et al., 1999; Moraes, Allard, & Patla, 2007; Moraes, Lewis, & Patla, 2004; Moraes & Patla, 2006). The three proposed determinants are comprised of: 1) minimum foot displacement, 2) stability, and 3) maintenance of forward progression. These collective works have indicated that environmental constraints appear to influence the priority and weight placed upon each determinant.

The following protocols discussed will focus on the aforementioned works (Patla et al., 1999; Moraes et al., 2004; Moraes et al., 2007) and will be reflected in the methodology of the current study. As shown in Figure 2 all of the studies presented an obstacle at varying orientations to where the natural right-footfall position occurred during straight walk through trials. The "obstacle" was comprised of a cutout placed on the ground or a rectangle projected onto the path. The results between the various paradigms are compared regardless of any differences in the perceived ‘risk’ the various obstacles may pose to the individual. While avoidance behaviour when stepping over obstacles that are perceived as being more fragile has been shown to be more conservative (i.e. increased step toe clearance) (Patla, Rietdyk, Martin, and Prentice, 1996); the use of 'virtual' planar obstacles was validated by Moraes and Patla (2006) where no behavioural differences in avoidance were found when comparing a projected obstacle to a hole of the parameters with a depth of 6cm.

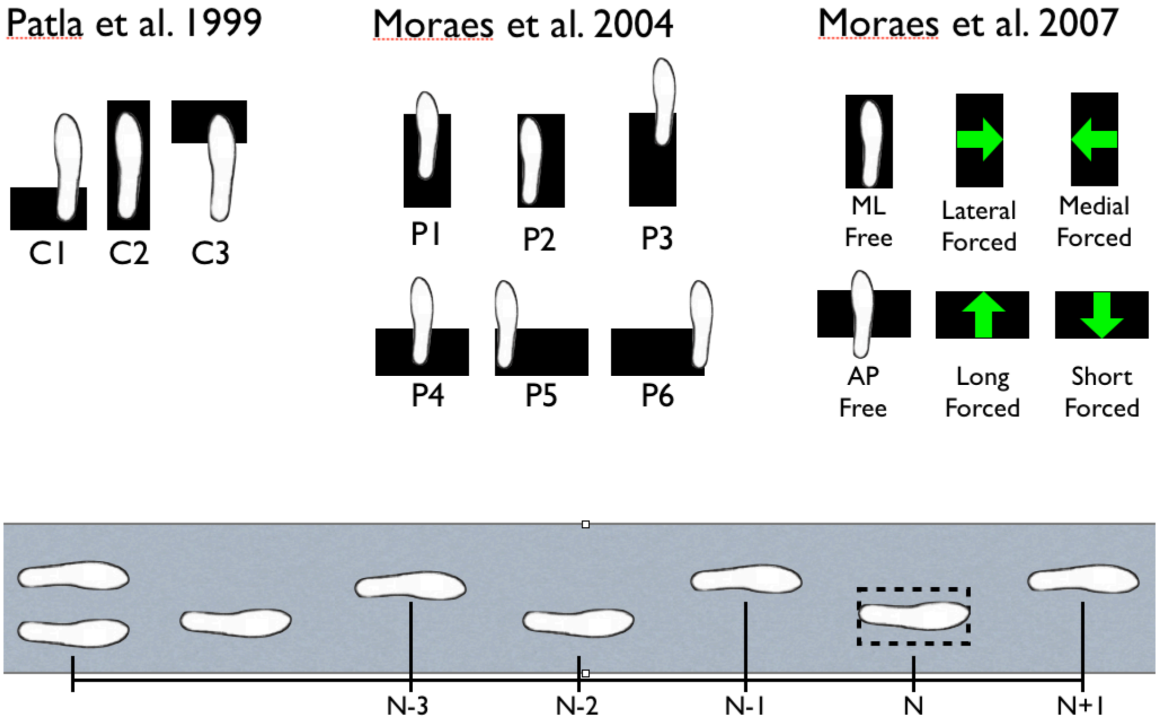

Figure 2. Adapted from Patla et al., 1999; Moraes et al., 2004; and Moraes et al., 2007. BOTTOM: General experimental set-up for the *Alternate Foot Placement* studies, where N is the location that the obstacle is presented in various orientations to the natural footfall (determined during straight walk through conditions) and the additional foot placements along the pathway are referred to relative to position N. TOP: obstacle positioning relative to normal foot placement (right foot outline) at position N during straight walk through trials.

Methodological Summaries

Patla et al. (1999):

The participants were given a 12m long pathway to walk. The start position was adjusted so that the obstacle was illuminated beneath a plexiglass surface about halfway along the path and triggered a pressure sensitive mat in the preceding step. In what they term as Experiment 1, there is a temporal component added to a couple of the obstacle orientations. All of the obstacle orientations appeared at contralateral foot contact (CFC) for ten of the trials. Orientations 1 and 2, where the obstacle fell across the hind part of the natural foot placement and along the entire length of the footfall respectively, also had ten trials allocated to temporal delays of 100 and 200 ms following CFC.

Moraes, Lewis, and Patla (2004):

Participants walked along a GAITRite mat (366 x 61 cm) ten times at a self-selected pace. The obstacles were placed at the fourth foot placement based on the average foot placement during the straight walking conditions and were visible from the start of each trial. Six of the participants were given a spatial constraint where they were required to step on a target (30 x 15 cm) in the step preceding the obstacle avoidance.

Moraes, Allard, and Patla (2007):

The pathway that participants were asked to walk along contained a force plate and a liquid crystal display (LCD) monitor embedded beneath a layer of plexiglass. The initial starting position was adjusted so that the (entire) left foot landed on the force plate and the following step had the right foot land in the centre of the LCD screen. Heel contact (vertical component >5 N) on the force plate triggered the appearance of the obstacle on the LCD screen. The obstacles allowed for either free avoidance or a specified direction (forced direction) to make the avoidance step. The Forced conditions involved cueing the participant to step in the direction of the dominant alternate foot placement and in the opposing direction of the dominant choice (i.e., the AP obstacle, wider than long, had a dominant adjustment of lengthening the step over the obstacle during the Free condition. For the same obstacle shape there was then a Forced long obstacle and a Forced short obstacle.

It was through these various manipulations of the general methodology Patla, Moraes, and colleagues attempted to validate the hierarchy of determinants for alternate foot placement (minimum foot displacement, stability, and maintenance of forward progression) proposed by Patla et al. (1999).

Rational for Determinants

Based upon the displacement between the normal landing spot to the alternate landing for long, short, medial, and lateral adjustment, it was proposed that the minimal displacement was a primary criterion in the selection of alternate foot placement. As shown in Figure 3 the dominant choice always occurred in a direction that involved a minimal foot displacement, regardless of any temporal constraint placed on the obstacle appearance.

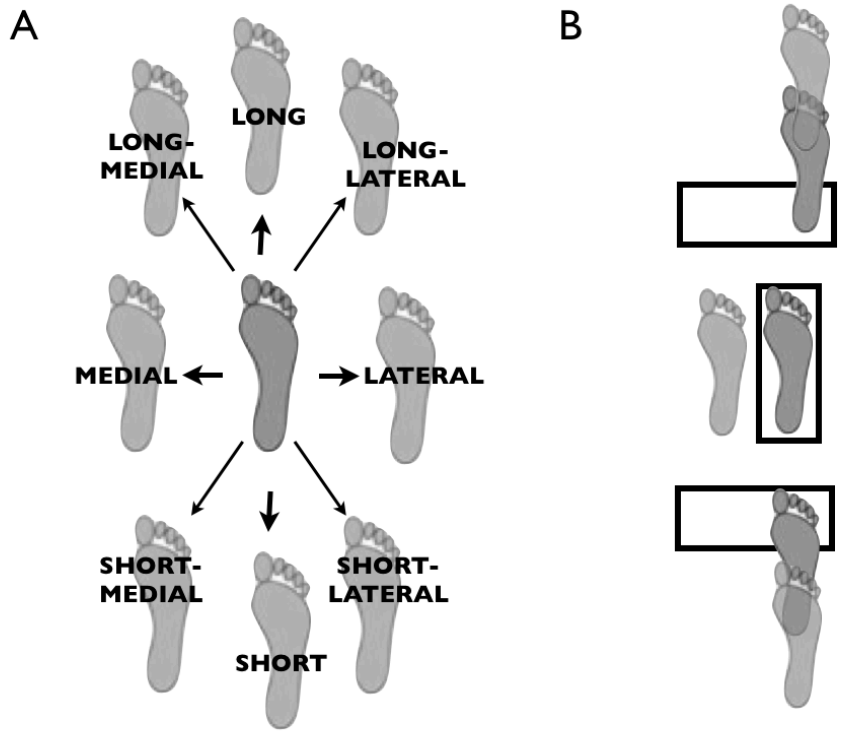

Figure 3. A: Eight possible alternate foot placement locations surrounding the normal foot placement (solid footprint). B: The dominant selection (darker footprint) compared to the foot placement during straight walking (light grey footprint) when obstacle (outlined rectangle) is presented (top to bottom is C1, C2, and C3). Figure adapted from Patla et al. (1999).

All obstacle positions had at least two possible directions of avoidance that would result in the same amount of displacement from the natural footfall**,** leading to the proposal of further determinants**.** When given the option between making adjustments to step length or width, as shown for Obstacles 1, 3, 4, and 6, the modulation of stepping in the plane of progression (stepping long or short) was preferred. Patla et al. (1999) suggested that maintenance of forward progression also held true when avoidance choices had equal minimal displacement between lateral and medial avoidance. Medial stepping was found to be the preferred strategy and argued to be the more beneficial behaviour when considering forward progression across the avoidance and following compensatory step.

The third determinant of stability was inferred from the findings that when selecting between lengthen or shortening a step to satisfy minimal displacement, the later was dominantly performed. However, when a step is shortened there is an increased risk of tumbling and/or falling, as the linear momentum of the body is converted to angular momentum if the COM is not properly controlled. While such consistent dominant avoidance behaviour lent credence to the proposed determinants of alternant foot placement, it was concluded that the protocol used was limited in the information to be gained to validate these assumptions. It was suggested that better measures of foot placement and stability (i.e. through the use of kinematic markers to determine foot position and the relative position of COM) would provide validation and insight as to how the determinants are weighted during alternate foot placement selection.

To validate and account for temporal and spatial influences on alternate foot placement, previous findings were abridged into a hypothesized decision algorithm by Moraes, Lewis, and Patla (2004). Temporal influences were inferred by comparing the responses observed in the study by Patla et al. (1999), when the obstacle was presented during the step preceding the avoidance, to their altered paradigm of having the obstacle placed on the path before the participant began each trial (4 steps away). Half of the participants were spatially constrained by a target to step upon that was placed at the step before the obstacle.

It was found that regardless of having the previous step constrained, the dominant alternate foot placement was not affected (Moraes et al., 2004). While the avoidance behaviour did not change when the spatial constraint was introduced, the magnitude of adjustment significantly decreased when participants were forced to perform the avoidance within one step cycle. It appeared that the subjects made use of the preceding steps in the unconstrained condition to parse out the adjustment and increase the margin of avoidance compared to the constrained condition.

Once again the dominant behaviour for the many of the obstacle placements (P1, P2, and P4) agreed with a direction that would require the least displacement from the natural footfall. However, when a dominant alternate foot placement was observed to differ from the least displacement (P3, P5, and P6, where ML adjustment would satisfy minimal displacement followed by stepping long), it was noted that the preferred alternate foot placement was made in the direction that was ranked the second smallest in displacement. Thus, it was suggested that while minimal displacement may play a role in dictating the alternate foot placement, it is not the primary determinant.

It is important to note that in the study by Patla et al. (1999) the alternate foot placement was characterized into eight possible directions, where in the Moraes et al. (2004) methodology there were six categories. Where the later used long, short, medial, lateral, and combinations thereof, the former study considered used long, short, and divided medial and lateral stepping into long and short components. If the medial-long and medial-short selections in the study by Moraes et al. (2004) were collapsed into a solely medial category, analogous to that measured by Patla et al. (1999), then the dominant behaviour always matched minimal displacement. Therefore, the number of alternate foot placement categories appeared to directly influence how the researchers interpreted the primacy of minimal displacement as a dictating factor in alternate foot placement selection.

When the minimal displacement bias was equal between stepping medially or laterally, participants chose to step medially (66% for unconstrained and 57% for the constrained condition). It was argued that the ability of the participants to anticipate their avoidance likely allowed them control their COM so that stability is maintained while stepping medially during avoidance and during the subsequent step (often a cross-over) and COM acceleration in the frontal plane is minimal (Moraes, Lewis, & Patla, 2004). The decrease in proportion for the constrained condition was reflected by an increase in stepping laterally.

Moraes, Allard, and Patla (2007) introduced a new manipulation that allowed for the analysis of movement in both the preferred and non-preferred direction. In addition to the Free stepping condition, analogous to the obstacles in previous studies, where the participants were free to choose their alternate foot placement, a Forced condition was introduced. Two obstacle orientations were used; 1) AP (30.5 cm wide by 13.5 cm long, shown to result in participants lengthening their step over the obstacle) and 2) ML (13 cm wide by 38 cm long, where medial avoidance has been previously observed). Each obstacle orientation had two Forced conditions, with an arrow on the obstacle indicating (in the direction of preferred stepping or in the opposing direction) where the participant should step. Obstacle appearance on an LCD monitor was triggered in the preceding step by heel contact (vertical component >5 N) on a force plate embedded in the pathway. Participants were able to perform the Forced condition successfully. The least errors occurred when the direction indicated matched the preferred dominant response performed during the Free condition. Unlike the previously observed medial preference when stepping displacement in the frontal plane is equal for alternate foot placement (Patla, 1999; Moraes et al., 2004), Moraes et al. (2007) observed a preference for lateral stepping during the Free condition and an increase in the error rate when cued to step medially than laterally during the Forced condition.

Specialized Populations: Athletes

The ability to couple perception with action is often indicative of ones ability to successfully navigate the ever changing environment. Athletes, as a population, are routinely confronted with settings that have an increased complexity than those experienced during day to day life and as a result are adept at coping with the challenges presented in an efficient manner (e.g. avoiding collision with opposing players, intercepting or hitting a ball, timing a tackle, etc.). While the recurrent practice of obstacle circumvention maneuvers may enable athletes to perform adaptive locomotion in a faster and more efficient manner than the general population, most research previously done has focused on identifying the relation between non-task specific visual processing abilities and expertise in sport (Fleishmann, 1966; Keele & Hawkins, 1982; Allard & Starkes, 1991); little research has investigated the performance of athletes in regards to obstacle avoidance and that which has been done focuses on circumvention (Gerin-Lajoie et al., 2007; Higuchi et al., 2011; Hackney, Zakoor, & Cinelli, 2005).

It is the assumption of superior avoidance skills that have driven the investigations on the efficacy of agility testing in regards to the ability to discriminate skill level among various players (e.g. netball, Australian football and rugby league) (Farrow, Young, & Bruce, 2005; Gabbett and Benton, 2009; Sheppard et al., 2006). Traditional tests of agility establish the ability to change direction with speed, this is termed a ‘closed’ skill as the action may be preplanned and does not encompass the additional cognitive demands that an athlete experiences during sport (Cox, 2002). Sheppard et al. (2006) suggested simple change of direction sprints lack the validity that open skill agility tests (i.e. direction changes in response to a cue) have in identifying skilled performance in field athletes and that agility should thus be defined by the change in direction in response to a sport specific stimulus.

Open skill agility tests incorporate the perceptual cognitive demands of response to a stimulus, where elite athletes have been shown to respond faster and complete the change of direction faster with greater accuracy. Such differentiating attributes were found for rugby league players ranging from novice to expert level who performed a reactive agility test, where they approached the experimenter at a sprint and responded to the direction in which the experimenter moved (this movement is sport specific as rugby league players would often have to intercept opponents and thus mirror the direction they cut toward). Decision time, measured as the onset of the experimenter movement and the first definitive step initiating the change in direction by the player. It was found that the higher skilled players had faster decision and movement times without sacrificing their response accuracy (Gabett & Benton, 2009).

Athletes are required not to just avoid single opponents in a game but must also navigate through a busy environment contain both opposition and fellow teammates.

Gerin-Lajoie et al. (2007) used a cluttered environment to test how athletes and non-athlete navigate to a goal, predicting that the athletes would minimize the medial-lateral distance from obstacles and maintain forward momentum. The authors varied the number of obstacles (10, 12, or 14 poles that were 1.45 m high by 0.3 m in diameter) with varying difficulty levels of obstacle placement (based upon global time to reach goal) between the start position and the goal. On straight walk through trials there was no difference in fast walking speed between the two groups. Regardless of the number of obstacles or the difficulty of placement, the athletes completed the task in significantly shorter times than the non-athletes. The medial-lateral distance to the obstacle was not found to be different between the groups. It was the ability of the athletes to navigate at a speed closer to their maximum unobstructed speed that resulted in their shorter completion time (i.e., forward momentum was maintained) and not a difference in the path taken (i.e. passing closer to obstacles to shorten the path length). It was suggested by Gerin-Lajoie et al. (2007) that the athletes were able to process visuo-spatial information faster than the non-athletes, a conclusion that is congruent with the previously mentioned literature, allowing the athletes to optimize the speed at which they traversed to the goal.

Specialized Populations: Dancers

Dance is another form of physical activity that develops strong perception-action coupling in addition to; fluid movement of joints, good coordination, and muscle tone (Federici, Bellagamba, & Rocchi, 2005). Dance expertise is qualified into varying levels of proficiency judged according to the performers physical virtuosity (e.g., limb coordination, flexibility, and strength) and subjective esthetic elements (Bläsing et al., 2012). By and large, the literature pertaining to the benefits of dance training on postural control and gait focuses on intervention-based paradigms involving those over the age of 50 and conjunctively with those suffering from neurodegenerative diseases that impair balance (i.e., Parkinson's disease).

While the literature on dynamic balance in dancers is sparse, static stability appears to be well characterized and provides a solid foundation of evidence to warrant future investigation of the more complex task of adaptive locomotion (Rougier et al., 2003). Common measures of static balance that involve manipulating visual input by having participants balance with their eyes open, followed by eyes closed or changing the base of support have been used to characterize the effects of dance training, specifically ballet, on balance control. When the base of support is reduced to one foot, greater balance control has been found in professional dancers compared to those with less to no dance training (Hugel, Cadopi, Kohler, & Perrin, 1999; Rein et al., 2011). Greater balance control, as measured by sway area and amplitude, was found for dancers compared to non-dancers by Stins and colleagues (2009), regardless of widening the base of support to shoulder width. However, there is a small cohort of literature that identifies superior postural control in dancers during eyes closed conditions but not when eyes are open (Golomer et al., 1999; Hugel et al., 1999). In contrast, Pérez, Solana, Murillo, and Hernández (2014) recently found that when measuring the complexity of postural control (i.e., sample entropy and permutation entropy) between contemporary dancers and non-dancers that comparatively the dancers had better postural faculty only when their eyes were closed.

These measures of static balance and their findings are incongruent amongst the literature, this is in contrast to the consistent gains that are repeatedly observed (e.g., improved Tinetti and Romberg scores, reduced sit-up-and-go times, decreased COP displacement, etc.) when older adults are given dance-based interventions (Federici, Bellagamba, & Rocch, 2005; Shigematsu et al., 2002; Sofianidis, Hatzitaki, Douka, & Grouios, 2009). This evidence, substantiates the need to widen the scope of research to include dynamic measures, as the findings during quiet standing are conflicting and lack any strong indication differences due to dance training in healthy young adults.

Dance may entrain a shift from the use of vision to the use of proprioceptive input during multi-modal integration during locomotion that is not pertinent for postural control during static stance (Bläsing et al., 2012; Golomer & Dupui, 2000). Though the relative weighting of visual input to proprioception may be lessened, Panchuck and Vickers (2011) aimed to characterize the differences in gaze behaviour between elite ballet dancers and controls (having no dance training beyond a recreational level), believing that the ballet dancers would exhibit the same ‘quiet eye’ gaze strategies that have been observed in other ‘elite performers’ (i.e., golfers, hockey goaltenders, rifle and shot gun shooting, billiards, etc.)(Causer et al., 2010; Janelle et al., 2000; Panchuck & Vickers, 2006; Vickers, 1992; Williams et al., 2002).

The quiet eye, defined as the final fixation or tracking gaze located on a specific object before the execution of the movement deemed responsible for success, is inferred to be indicative of focus characteristics during gaze and has an earlier onset and duration in the elite (Vickers, 1996). Panchuck and Vickers (2011) used a paradigm that had their participants approach (2-3 m), cross, and exit a 3 m distance with varying constraints on the width of their base of support; 1) free foot placement during straight crossing, 2) stepping along a line (width 10 cm), and 3) stepping along a narrow line (width 2.5 cm). Their rationale was that the increased reliance on visual information when the base of support is reduced during quiet stance would be mirrored during the crossing and a longer duration and frequency of quiet eye fixating straight ahead would differentiate the elite ballet dancers from their controls (Panchuck & Vickers, 2011; Streepey, Kenyon, & Keshner, 2007).

As expected, the ballet dancers exhibited fewer fixations of greater duration and held their quiet eye (the fixation made prior to stepping into the line from the approach) significantly longer than controls. However, this stereotypic behaviour was not mirrored by what was considered ‘successful’ behaviour. The ballet group did not step upon the line with any greater precision than their untrained counterparts. Panchuck and Vickers (2011) offer two suppositions; 1) the inherent degree of turnout impacted the reliability of their measure of precision, as they used the distance of both the heel and ball of the foot from the center line, 2) the ballet group may have released more degrees of freedom under their feet in consequence of their forward fixation. The second measure of gait considered was the amount of relative time each group spent in the approach, crossing, and exit phases. The dancers were found to step faster during the approach and crossing, and slower during the exit, juxtaposed by the slow crossing and quick exit made by the control group.

It is important to consider that these two measures conjunctively may suggest that dancers displayed a more ‘successful’ performance in regards to Fitts’ Law. The speed-accuracy trade-off established by Fitts (1954), seminally exhibited by performance on a reciprocal tapping task, is preserved during visually guided stepping and was apparent for the ballet dancers and the controls by the decrease in stepping precision while stepping duration remained unaffected when comparing the 10 cm to the 2.5 cm widths, respectively (Drury & Woolley, 1995; Panchuck & Vickers, 2011). As the change in ‘target’ width elicited a change in accuracy while the temporal component remained invariable, the effect of extensive ballet training demonstrates greater skill by the reduced time used to complete crossing along the line at no cost to precision of stepping when compared to the control group.

As the instructions given to the participants indicated that they should walk to the end position at a comfortable pace, it is interesting to note that the dancers intuitively completed the task at a faster speed regardless of restrictions on their foot placement. It is proposed that when presented with a planar obstacle(s) along their travel path, that dancers would similarly value forward progression and dominantly choose medial avoidance. However, based on the previously discussed literature, it would appear that dancers may be a population to which medial stepping does not pose a risk to stability.

Specialized Populations: Athletic Training in General

Recalling the dynamics of perception and action proposed by Warren (2006), where there is a circular relationship between the agent and the environment, the question arises whether it is the gathering of information, the ability to act upon the environment, or both that athletes are proficient in to be able to perform complex tasks better than their non-athlete counterparts. Abernathy et al. (1994) concluded that the difference between novice and expert athletes performance on generalized tests of perception, cognition, or motor control is a function of the experts having superior processing and not attributed to their physical characteristics. The perceptual and cognitive differences between novice, intermediate, and expert athlete was categorized into three levels by Ackerman (1988), where one has to master the abilities in one level before they progress (Figure 4). When comparing athletes, or arguably dancers, to non-athlete populations it is important to remember this hierarchy of abilities to efficiently use this comparison of populations to tease out perceptual influences on performance.

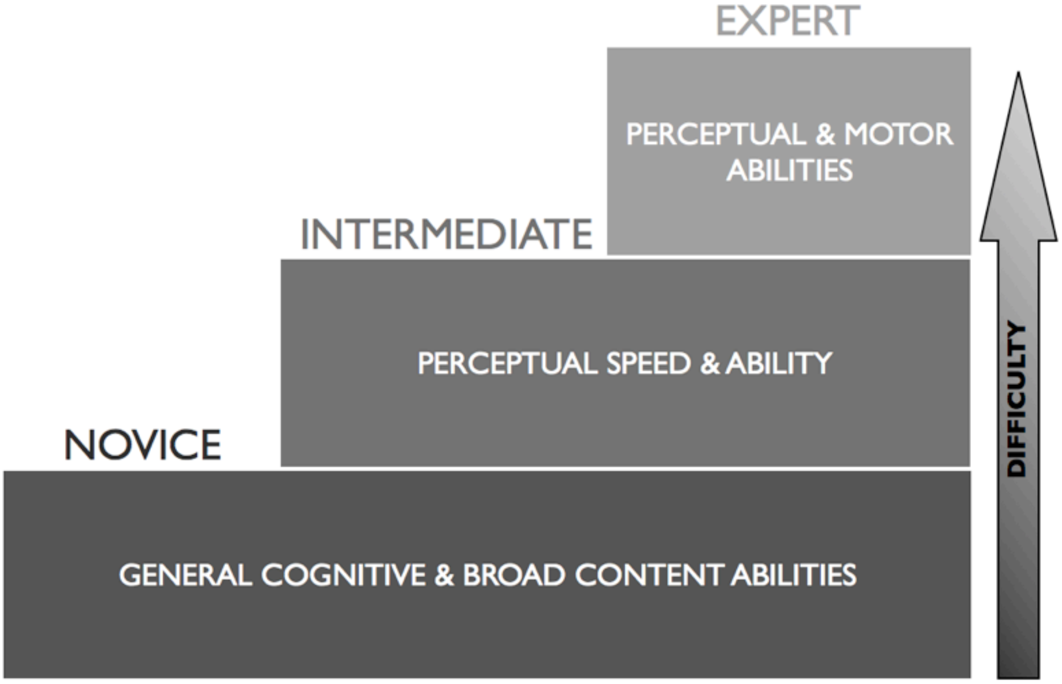

Figure 4. Perceptual and cognitive tiers encompassed as the level of athletic expertise increases, as proposed by Ackerman (1988).

Recall, it was suggested that athletes have superior processing during circumvention of numerous obstacles that appears to be coupled with the ability to maintain forward momentum. Dancers also appear to value speed of progression without detriment to the preservation of stability. As such these two populations may aid in further discerning the control laws dictating the preferences during alternate foot placement since conflicting preferences for stepping medially or laterally when avoiding a planar obstacle have been found for young adults (Patla et al., 1999; Moraes et al., 2004; Moraes et al., 2006; Moraes et al., 2007). The rationale for the selection of medial over lateral is maintenance of forward progression and stability, respectively. The maintenance of forward momentum can be considered to be counterbalanced with stability in regards to medial-lateral movement during bipedal gait. The inclusion of athletes and dancers in the current study was based on the value both groups place upon the maintenance forward progression and thus it was predicted that they would select medial avoidance to a greater degree than non-athletes, further validating the determinants initially put forward by Patla et al (1999).

The Current Study

It has been well documented that, when it involves comparatively minimal displacement, stepping long is preferable to avoid a planar obstacle as in maintains forward momentum and stability in the A-P direction. Slight manipulations in obstacle position and orientation in relation to foot placement at N have aided in segregating the degree of influence between maintaining forward momentum and satisfying minimal displacement in the determination of the alternate foot placement. However, conflicting stepping strategies (medially or laterally) about a planar obstacle as the dominant response has hindered the ability for the researchers to identify determinants in a similar manner. The objectives of the proposed study are to determine the control laws that guide location of alternate foot placements through the manipulation of the amount of visual information prior to the appearance of obstacles and the addition of a second obstacle placed sequentially along the travel path. In addition, the current study use an athletic and a non-athlete population to determine the contribution of training in regards to the rank of maintaining forward progression to stability in determining preferred alternate foot placement.

It was expected that the addition of a secondary obstacle would increase the challenge to dynamic stability and thus result in an avoidance strategy that would incorporate or allow for the widening the base of support (i.e. ML or LM alternate foot placement). The other possible avoidance about the two obstacles (Medial-Medial (MM)) was predicted as a strategy that would place value on forward momentum; a strategy that would resound with the training that dancers and field athletes receive and were predicted to be selected by these individuals for a great proportion of the trials. As it was presumed that the two steps before the obstacles would temporally be the most important time as to when the visual information is gathered and the point at which alternate foot placement is determined. It was hypothesized that this would be reflected by the preservation of the dominant alternate foot placement between obstacle presentation at steady state versus delaying the appearance to when the individual is two steps away; while those measure of gait that significantly determine the selection between possible directions of avoidance will be prevalent at this preceding two step mark.

Methods

Participants

The current study included 33 young female adults categorized into three groups based upon their training in sport; 1) Field Athletes (FA) (n=11, age= 22± 2.68 years), 2) individuals with dance training (DT), and 3) Non-Athletes (NA). Three of the FA played at the varsity level for Wilfrid Laurier University, one of them belonged to the Women's Lacrosse team and the other two from the Women's rugby program. The remaining FA were in season playing for the Waterloo County Women's Rugby team ranked first in the the premier league in Ontario at the time they participated in the study. Of those, 6 were also members on the varsity teams at the universities they attended (four at the University of Waterloo and two additional players from Wilfrid Laurier University program). The NA had no previous participation in organized sport (e.g. varsity, intramural, or recreational) in the past 5 or more years (n=12, age= 21.75± 1.54 years). DT participants recruited from the Wilfrid Laurier Competitive Dance Team had on average 14.6 years of dance training with some previous and/or current training in ballet specifically (n=10, age= 21.1± 1.1 years).

Participants completed a health history questionnaire (see Appendix), to ensure an absence of cognitive or bodily injury prior to the experiment; the sport, length of participation in organized sport, and incidence of a diagnosed concussion within the past 6 months were also included within the questionnaire. All participants were female and had normal or corrected-to-normal vision, free of any physical limitation(s) affecting ability to walk the 15m path, had no known neurological impairments, and could read and understand English instruction. The current experiment has received ethical approval from the Wilfrid Laurier University Research Ethics Board (REB #3851).

Seven individuals that participated in the current study are not listed above with the other participants as their data was excluded *post hoc*. A subject that would have been considered a non-athlete was excluded due to being in the 7th month of gestation. Three individuals were excluded due to possible lingering effect of a possible previous concussion (i.e. two affirmed suffering from a concussion and the other was unsure) and had experienced headaches and balance problems in the 6 months previous to their participation in the study. Three additional participants were excluded based upon having previous dance training in addition to participation in sport.

Experimental Design

In order to track the participants through space they were outfitted with 3 rigid bodies, consisting of 3 infrared emitting diodes (IREDs) in a triangular formation. These rigid bodies provided a reference point to allow for the digitization of anatomical locations (see Figure 5). One rigid body was placed near the midline of the trunk below the xyphoid process to bilaterally mark the glenohumeral joint (GH) and the anterior superior iliac spine (ASIS); and each leg had a rigid body placed anteriorly on the distal portion of the tibia. Three OPTOTRAK cameras (Northern Digital, Waterloo, Ontario, Canada) positioned in front of the participants were used to track the IRED markers at a sampling frequency of 60 Hz.

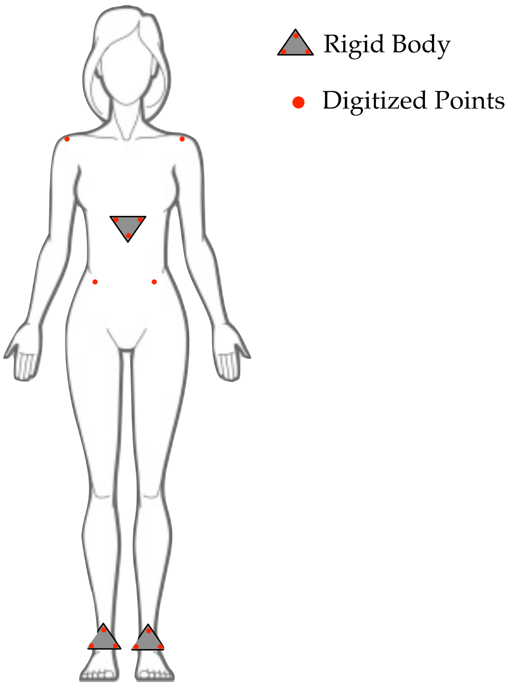

Figure 5. Location of rigid bodies and digitized points used to represent the body in space.

The experiment was conducted within a room where the path was unconfined (13m by 6m) but defined by the start position of the participant and the goal, as instructions dictated for participants to walk to the goal. Prior the start of experimental trials participants were instructed to walk to the goal, 13 meters ahead, at their normal pace (Figure 6). A data projector mounted from the ceiling was used to project two consecutive planar obstacles, which appeared as black rectangles (15cm wide by 70cm long) on a background of the carpet approximately 8m from the start position. The start position was adjusted to a distance that allowed the participants comfortably walk at their selected pace while the foot placements landed near the centre of the obstacles. To keep foot placement in the anterior/posterior (AP) direction fairly consistent when walking through the projection area (~1.5m long, able to fit two steps) two strips of low contrast tape leading up to the projection were used to mark where the preceding two steps (the markings were adjusted by the experimenter to their stride length and their natural footfall location) should occur. Participants were informed that these markings were not to be stepped on precisely but to provide general guidance of step length to prevent leaping over obstacles.

The tape markings were found to be prudent, as pilot work had shown that some participants were highly variable in their foot placement leading up to the projection and when the natural footfall was near the ends of the obstacle(s) the preferable avoidance behaviour was to step short or leap over the obstacles. The observed preference of individuals to lengthen and/or shorten their steps to avoid the obstacle over adjustment in the medial-lateral direction was so strong that the entire projection length was utilized to prevent this from happening. While the width of the obstacle(s) (15 cm) was consistent with the previous alternate foot placement paradigms (Patla et al., 1999; Moraes et al., 2004; Moraes & Patla, 2006; Moraes et al., 2007; respectively 14 cm, 20 cm, 12.5 cm, and 13.5 cm) the length of the obstacles (70 cm) allowed for some anterior-posterior variability in the steps preceding the obstacle while maintaining the natural footfall within the obstacles to a degree that the preferred direction of alternate foot placement was in the medial-lateral direction (the direction of avoidance that the current study was specifically testing).

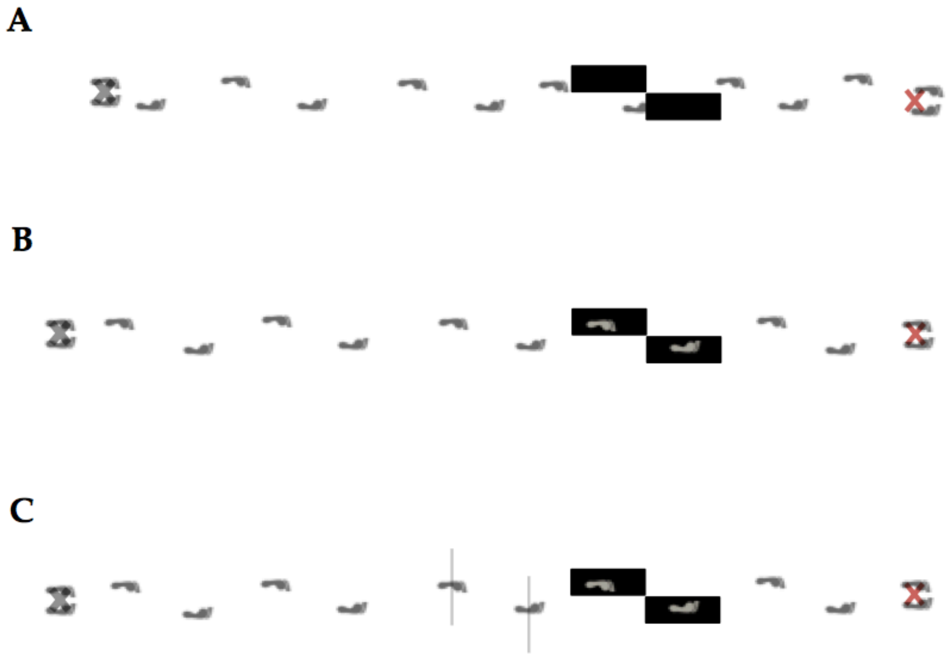

Figure 6. A: Straight walking from start to goal to determine approximate foot placement in relation to where the obstacles are projected onto the floor. B: Walking from various start positions until participant consistently stepping on both obstacles at a comfortable speed and stride length. C: Placement of ‘target’ strips of low contrast tape at the two average step positions preceding the obstacles.

This straight walking task was performed repeatedly until comfortable tape markings were determined. On the subsequent 5 trials a random appearance of all conditions (Figure 7) where the participants were instructed to avoid stepping on any obstacles if/when they appeared (without jumping, leaping, and/or stuttering the steps) while continuing onto the goal; the participants were able to become familiar with the obstacle(s) and the possible timing of their appearance. The participants experienced 3 possible appearance conditions randomly presented: 1) Double obstacle at steady state (DSS) where both obstacles appeared after participants reached steady state (i.e. ~3 steps from start); 2) Delayed double obstacle appearance (DDEL) where both obstacles appeared when participants reached N-2; and 3) Single obstacle appearance (SIN) where just the obstacle at N appeared when participants were 2 steps away. Each participant performed 48 randomized trials, 50% of which had no obstacle (NO) and they walked through to the goal and the rest of the trials evenly distributed between the three appearance conditions. Steady state appearance was triggered around the third step to ensure that 100% of the selected pace had been reached; this assumption based upon the knowledge the about 85% of of final steady state velocity is reached at the first heel contact following gait initiation (Winter, 1995). In addition, this timing allowed for at least two steps for the participants to parse out their locomotor adjustment to accomplish their preferred avoidance behaviour.

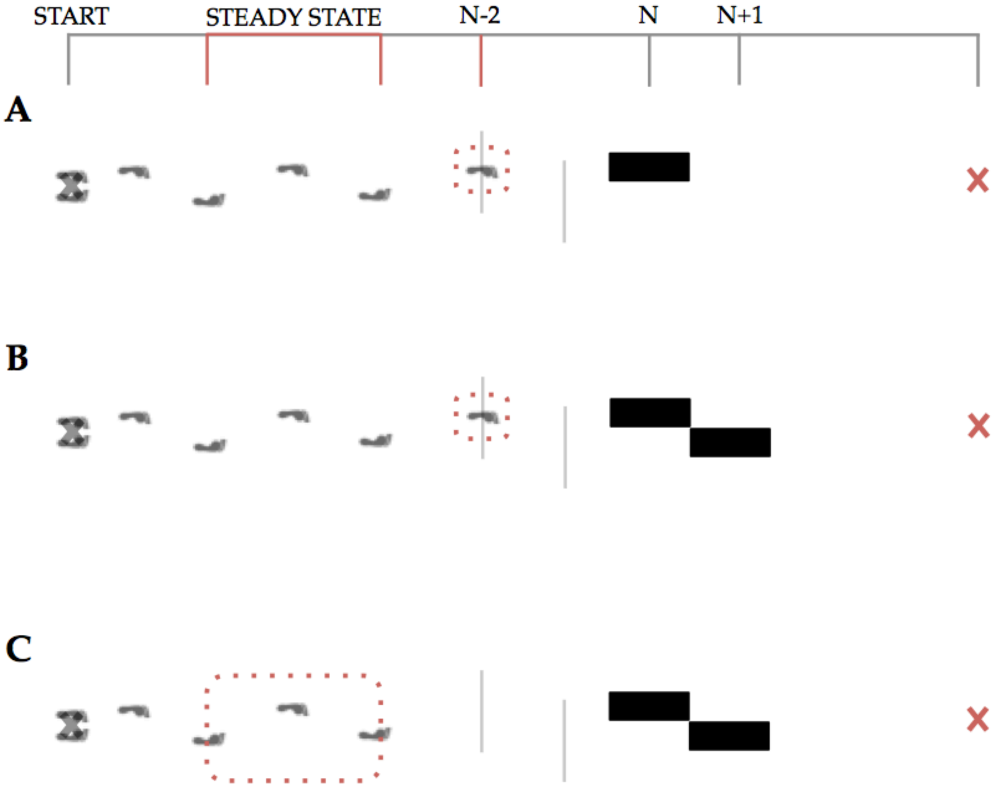

Figure 7. Experimental obstacle conditions; A: Single obstacle (SIN), B: Double obstacle with delayed appearance (DDEL), and C: Double obstacle during steady state (DSS). Red markings indicating the point in the progression (grey footprints) from the start to the goal that the appearance of the obstacle(s) (black rectangles;15cm x 70cm) was triggered.

Data Analysis

The centre of mass (COM) for each participant was estimated using a weighted average of all Optotrak markings (i.e. 46% allocated to the upper trunk (average of the left GH, right GH, and Xyphoid markers), 22% from an average of the bilateral ASIS markers, and 16% for each leg segment (0.625*ASIS + 0.375*ankle)). Anecdotally, participant during pilot testing (and during the experiment) did not use their arms to maintain or regain balance (i.e. they did not flail or raise their arm and maintained a normal arm swing), thus it was assumed that arm movements would contribute negligibly to the COM movement and the lack of arm inclusion in the weighted COM calculation would not significantly decrease the quality of the measure.

The velocity of the COM calculated as the displacement over time during the approach was run via low pass Butterworth filter (4th order with 4 Hz cut-off). The velocity of the approach was averaged from when markers became visible (~3.7 m) until heel contact at N-2 (~1.2 m)(the origin was set where the inner corners of the rectangles met), for this region variability of the COM in the ML plane was also calculated.

The minimum Dynamic Stability Margin (DSM) was calculated as the absolute minimum medial-lateral distance during single support (i.e. from toe-off to heel-contact of the contralateral foot) between the position of the anterior ankle rigid body and the COM trajectory for N-2 and N-1 (Figure 8). Greater separation between the COM and the lateral border is an indicator of better stability due to the greater leeway given for the implementation of compensatory strategies (Pai & Patton, 1997).

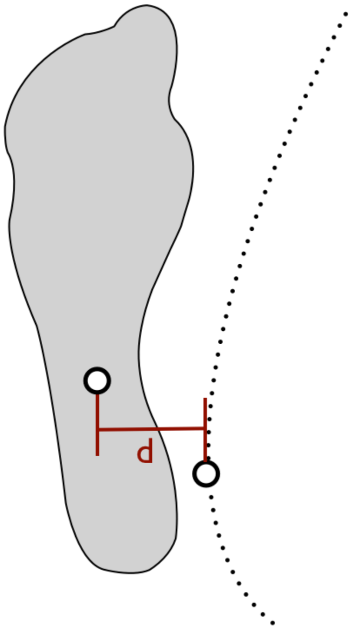

Figure 8. Minimum Dynamic Stability Margin (DSM) calculated as the absolute minimum ML distance (d) of the Centre of Mass (COM; circle sitting upon the dotted line the represents the COM trajectory during single support) from the ML position of the anterior ankle rigid body (white circle on the foot) during single support (i.e. from toe-off to heel-contact of the contralateral foot).

Behaviour selection was observationally categorized according to the foot placement relative to the obstacle(s). For the SIN condition foot placement at N was determined to be either medial or lateral to the obstacle. When double obstacles conditions occurred there were three possible behaviour categories; medial-medial (MM), medial-lateral (ML), or lateral-medial (LM) (lateral-lateral was not possible as participants were instructed not to leap over obstacles), named respective to the avoidance at N and N+1.

Statistical Analysis

A multi-variate ANOVA was performed on those participants that choose only to step Medial-Medial (MM) regardless of the double obstacle condition, approach velocity, ML COM variability, ML foot placement (FP) at N-2, and minimum DSM at N-2 and

N-1 were compared between the three groups (NA, FA, and DT). Since no significant differences were found between the groups subsequent analysis collapsed the participants into a single pool of participants; paired t-tests were performed for the aforementioned gait parameters across the steady state and delayed appearance of the double obstacles. To compare those who only stepped MM during double avoidance to those that solely made ML avoidances a 2 x 2 ANOVA for double obstacle condition by avoidance strategy with repeated measures on the latter was run for minimum DSM at N-2 and N-1, ML COM variability, and ML foot placement at N-2 and N-1.

Behaviour selection was transformed into a coefficient of unalikeability. Unalikeability focuses on how observations differ from one another and can be used to transform categorical data into a variable value interpreted as the proportion of possible comparisons which are unalike (Kader & Perry, 2007). As it was shown that the amount of time that the double obstacles were visible had a significant effect on various proposed determinants, Kendall’s tau correlations were run separately for the double obstacle conditions. Kendall’s Tau-b is suggested to be the best non-parametric correlational measure, was used due to the small sample size and since multiple participants implemented the same strategy for all trials resulting a null designation for unalikeability (i.e. large number of tied ranks) (Field, 2009).

To gain greater insight as to what gait parameter(s) were driving the selection of avoidance strategy (LM, ML, or MM) we treated each trial an independent observation; it was assumed that the gait parameters preceding the avoidance, regardless of the individual, that would dictate the avoidance strategy and thus could be considered separate to the participant. A MANOVA was performed on approach velocity, ML COM variability, minimum DSM at N-2 and N-1, and ML FP at N-2, where each observation was grouped by condition (DSS and DDEL) and behaviour (LM, MM, and ML).

Results

Single vs. Double Obstacle Avoidance

All participants, regardless of training, stepped medially to avoid the obstacle for every trial during the single obstacle (SIN) condition. When a second obstacle was introduced the same consistency in behaviour was not always observed. While close to half of the participants had consistent behaviour (n= 16), stepping Medial-Medial (MM) for both double obstacle conditions, the rest were variable in the number and proportion of avoidance strategies they used (see Appendix). Thus the initial analysis to determine the effects of visual conditions and training on gait parameters was investigated using those individuals that selected MM stepping, to control for behaviour.

Medial-Medial Avoidance: controlling for observed behaviour

As the design involved repeated measures of each condition and many individuals exhibited mixed selection of alternate foot placements (i.e. MM, ML, and/or LM) during the double obstacle conditions, it was thought that collapsing al of these trials would ‘muddy’ any influence that delaying the appearance of the obstacles might of had. Sixteen of the participants selected to step in a Medial-Medial (MM) avoidance during all trials for both the steady state appearance and when the appearance was delayed until N-2. Of those that always chose to avoid MM; six were Non-Athletes (NA), four were Field Athletes (FA), and six were trained in dance (DT). A multi-variate ANOVA was performed on approach velocity, ML foot placement (FP) at N-2 and N-1, ML COM variability, and minimum DSM at N-2 and N-1 to determine if there was a group effect of training. No significant difference between the Non-athletes, Field Athletes, or those with dance training was found for any of the tested measures. Based upon this, the subsequent analysis collapsed the three training groups together and compared the same gait parameter between the double obstacle conditions (steady state and delayed appearance; respectively DSS and DDEL) for each participant.

Paired t-tests were run between DSS and DDEL to determine the affect of changes in the temporal appearance of the obstacles on the proposed gait determinants (i.e. approach velocity, ML FP, ML COM variability, etc.) during MM avoidance behaviour. The analysis revealed significant differences for minimum DSM at N-2 (t(15) = 3.272, $p = 0.005$), ML COM variability (t(15) = 4.40, $p = 0.001$), and ML FP at N-2 (t (15) = -2.181, $p < 0.05$). When participants had more time to execute their avoidance they stepped farther from the midline at N-2 (DSS: M = -8.64, SD = 6.91; DDEL: M = -6.45, SD = 7.56); while maintaining their COM farther inside the ankle (minimum DSM at N-2; M = 6.414, SD = 2.528 for DSS and M = 5.089, SD = 2.107 for DDEL). ML COM variability was larger when the obstacles were presented during the approach (M = 5.373, SD = 3.513) compared to DDEL (M= 3.89, SD = 3.019). No significant differences were found for approach velocity, ML FP and minimum DSM at N-1.

Medial-Medial vs. Medial-Lateral Avoidance

A large proportion of the participants (61%) employed the same avoidance strategy for all conditions, regardless of the number of obstacles and when they were presented. Those that stepped MM were previously analyzed to provide insight to how the timing of presentation may have influenced various measures of gait. Additional analysis compared them to those who chose a ML avoidance behaviour; a 2 x 2 ANOVA for double obstacle condition by behaviour with repeated measures on the later was run for ML COM variability, minimum DSM at N-2 and N-1, and ML FP at N-2 and N-1. No significant differences were found for minimum DSM and ML FP at N-1.

Similar to the t-test in 'Medial-Medial Avoidance: controlling for observed behaviour', a main effect of condition was found for ML COM variability (F(1,18)= 18.31, $p< 0.001$) and ML FP at N-2 (F(1,18)= 18.31, $p< 0.001$). Where ML COM variability is significantly greater when the obstacles are presented earlier during the navigation to the goal (DSS: M = 3.929, SD = 1.63; DDEL: M = 2.996, SD = 1.29). Regardless of the observed alternate foot placement, individuals tended to step farther from the middle of the path (i.e. ML FP at N-2 more lateral) when having visual information of the available at steady state (M = -9.324, SD = 6.448) compared to having the appearance delayed until they reached N-2 (M = -8.234, SD = 6.456).

Main effect of avoidance was found for minimum DSM at N-2 (F(2.18)= , p=0.001). Where those that stepped ML had their COM travel closer to the outer edge of their base of support (M= 0.984, SD= 0.346) than those whom stepped MM (M=5.875, SD= 0.284).

Variable Avoidance Behaviour

While those that chose to maintain a consistent strategy when avoiding the obstacles during DSS and DDEL have been discussed, varying preference in the avoidance strategy primarily selected was found to be variable among the remaining participants (n= 13) and variable within-subject for the double obstacle conditions. If the average of the proposed determining gait parameters was taken for those individuals that exhibited mix avoidance behaviours then the likely reciprocal variability in these parameters would be washed out. Thus, avoidance strategy selection (i.e. the proportions of trials that the participant stepped Medial-Medial (MM), Medial-Lateral (ML), and/or Lateral-Medial (LM) during the steady state and delayed double obstacle appearance conditions) was transformed into a coefficient of unalikeability. Unalikeability focuses on how observations differ from one another and can be used to transform categorical data into a variable value interpreted as the proportion of possible comparisons which are unalike (Kader & Perry, 2007). This coefficient representing the variability in avoidance strategies used was correlated to the standard deviation of the proposed gait parameters to determine the strength of this hypothesized reciprocal relationship (i.e. the more unalike the behaviours were the greater the variability in the measure of gait should be). As it was shown that the amount of time that the double obstacles were visible prior to avoidance had a significant effect on various proposed determinants, Kendall's tau correlations were run separately for the double obstacle conditions. Kendall's Tau-b is suggested to be the best non-parametric correlational measure, was used due to the small sample size and since multiple participants implemented the same strategy for all trials resulting a null designation for unalikeability (i.e. large number of tied ranks)(Field, 2009).

Double Obstacle Steady State (DSS) Appearance

There was a moderate positive relationship between the variability in avoidance strategy selection with minimum DSM at N-1 (r = 0.359, *p*=0.002).

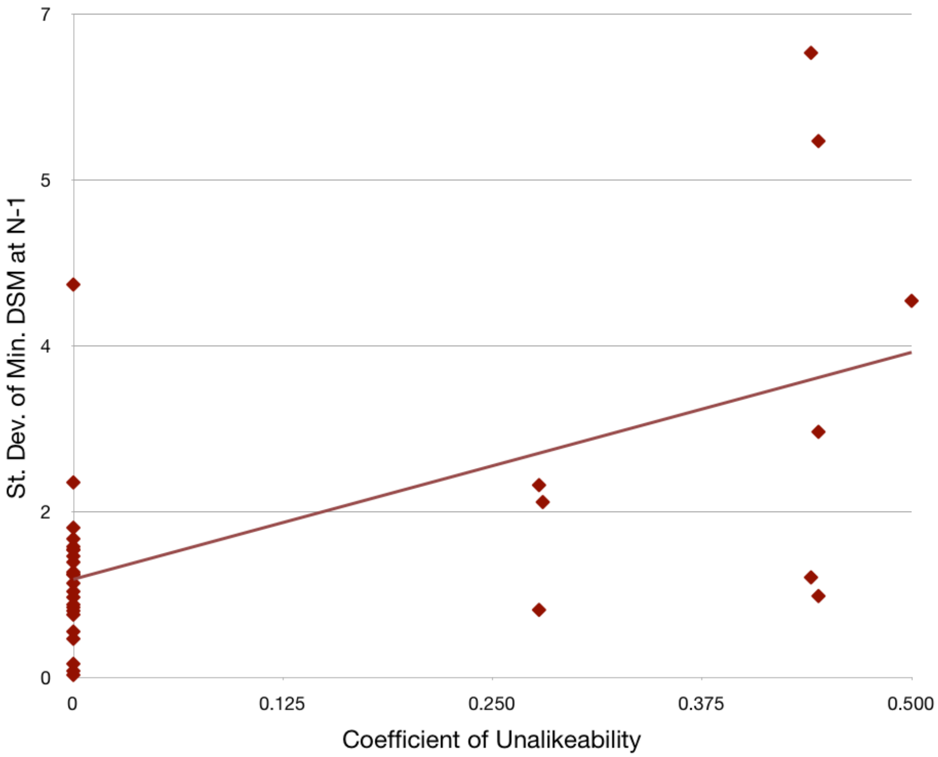

Figure 9. Kendall's correlation shows a significant positive relationship (r = 0.36) such that individuals who are more variable in their alternate foot placement behaviours are more variable in their minimum DSM at N-1.

Double Obstacle Delayed (DDEL) Appearance

There was a moderate positive relationship between the variability in avoidance strategy selection with minimum DSM at N-1 and ML COM variability (r = 0.441, *p*=0.002; r = 0.282, *p*< 0.05, respectively).

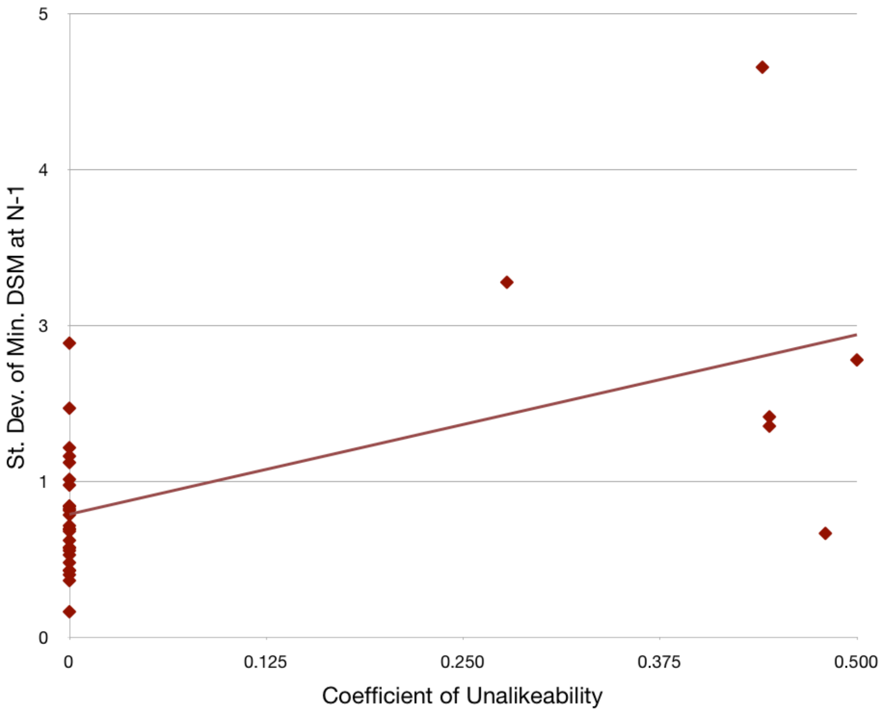

Figure 10. Kendall’s correlation shows a significant positive relationship (r = 0.44) such that individuals who are more variable in their alternate foot placement behaviours are more variable in their minimum DSM at N-1.

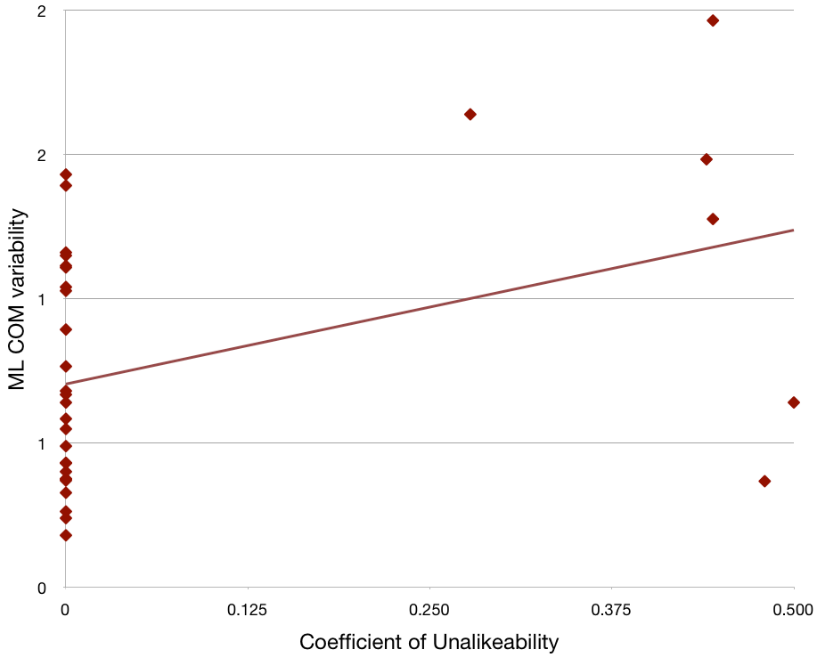

Figure 11. Kendall’s correlation shows a significant positive relationship (r = 0.28) such that individuals who are more variable in their alternate foot placement behaviours are more variable in their medial-lateral centre of mass variability.

Treating Each Trial as Independent

Traditionally, it is assumed that for a repeated measures design observations gained from a single participant cannot be independent of each other and treating them as such would discount the within-subject variability and artificially inflate the 'n'. If we assume that it is the gait parameters preceding the avoidance, regardless of the individual, that will dictate the avoidance strategy used then we propose that each trial may be treated as an independent observation. As such, a MANOVA was performed on approach velocity, minimum DSM at N-2 and N-1, ML COM variability, and ML FP at N-2 and N-1, where each observation was grouped by condition (DSS and DDEL) and behaviour (LM, MM, and ML).

Approach velocity (F(2,380)= 9.827, $p< 0.001$), ML COM variability (F(2,380)= 36.297, $p< 0.001$), Minimum DSM at N-2 (F(2,380)= 57.801, $p< 0.001$), and ML FP at N-2 (F(2,380)= 6.648, $p< 0.001$) were significantly related to the observed behaviour. Bonferroni pairwise comparisons reveled significant differences between LM (113.654 cm/s, SD= 16.099), ML (133.933cm/s, SD= 16.037) and MM (132.84 cm/s, SD= 16.908) approach velocities. MM and ML behaviours were found to have significantly different ML FP at N-2 (M = -10.13 cm ± 4.174 and M = -7.67 cm ± 7.478, respectively).

Medial-lateral COM variability differed significantly between ML (4.368, SD= 2.002) and the other avoidance strategies (LM: M = 1.715, SD=0.489; MM: M = 3.045, SD= 1.514). The minimum DSM at N-2 similarly differentiated the same behaviours (i.e. between ML (2.282 cm, SD= 3.063), LM (9.697 cm, SD= 3.322) and MM (5.396 cm, SD= 2.877)). No significant differences were found for the other measures (i.e. minimum DSM at N-1 and ML FP at N-1).

A main effect of condition was found for minimum DSM at N-2 (F(2,380)= 14.085, *p*< 0.001) where the COM of individuals was farther from the anterior ankle during DSS (5.374, SD= 2.908) than DDEL (3.89, SD= 3.019). Individuals also stepped more laterally at N-2 (F(2,380)= 6.648, *p*= 0.001) when presented with the obstacles sooner (DSS: M = -8.86 cm, SD= 6.89; DDEL: M = -8.14 cm, SD= 6.747).

The interaction between the obstacle conditions and elicited behaviour for the minimum DSM at N-1 (F(2,380)= 8.364, *p*< 0.001) is shown in the figure below.

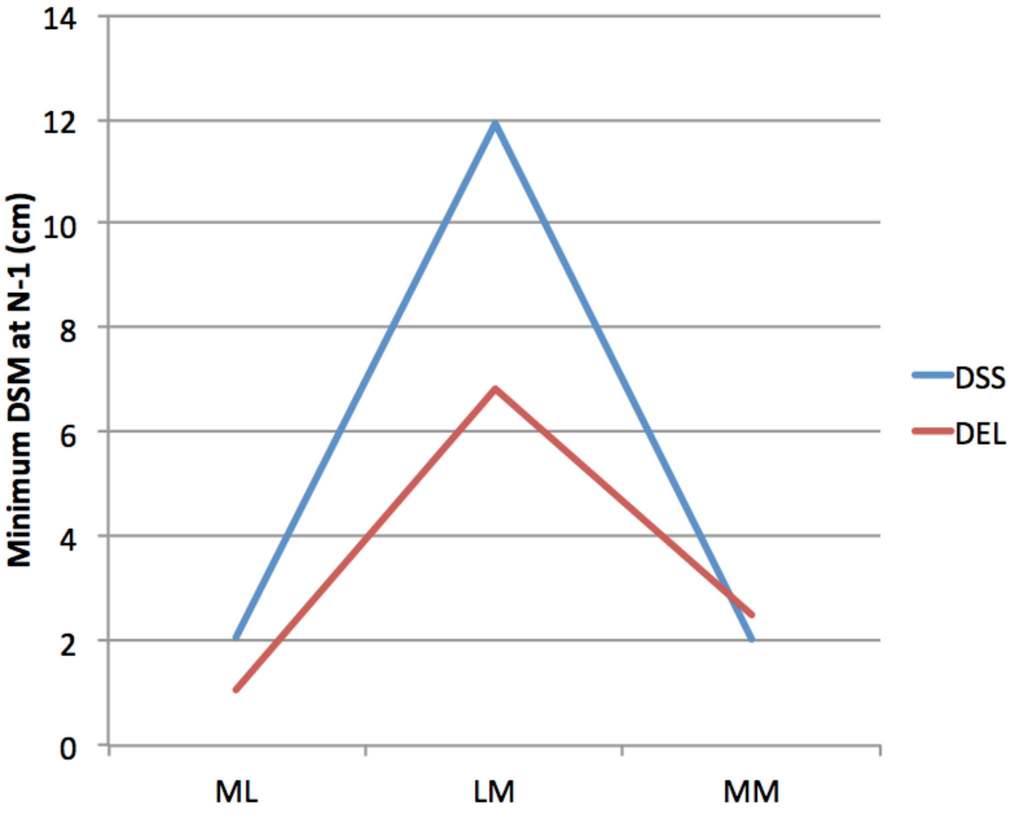

Figure 12. The interaction between the obstacle conditions and elicited behaviour (ML, LM, and MM) for the minimum DSM at N-1 (F(2,380)= 8.364, *p*< 0.001).

Discussion

The purpose of the current study was to determine gait parameter that dictate the location of alternate foot placements when required to avoid a planar obstacle(s) through the manipulation of the amount of visual information prior to the appearance of obstacles and the addition of a second obstacle placed sequentially along the travel path. In addition, the current study used athletic individuals (further divided in to those with dance training and those competing at a high level in a large field sport) and non-athletes to determine the contribution of training in the determination preferred alternate foot placement.

The three proposed determinants of alternate foot placement are comprised of: 1) minimum foot displacement, 2) stability, and 3) maintenance of forward progression (Patla et al., 1999; Moraes, Allard, & Patla, 2007; Moraes, Lewis, & Patla, 2004; Moraes & Patla, 2006). Kinematic measures of the participants as they approached the planar obstacle(s), including approach velocity, ML foot placement (FP) at N-2 and N-1, ML COM variability, and minimum DSM at N-2 and N-1, were analyzed as they were thought to have merit in their relation to the aforementioned determinants.

Dance and Athletic Training

No significant differences were found between the Field Athletes (FA), those with dance training (DT), or the Non-Athletes (NA) for any of the gait parameters tested. While the single obstacle condition was simplistic and thus predicted to be easily navigated by all of the participants, the inclusion of a subsequent obstacle (particularly the delayed appearance) of the double obstacle condition was thought to be challenging enough that differentiation of the specially trained groups (FA and DT) from the NAs would occur due to their presumed superior visuo-motor processing. Many perception-action skills require context specificity to be transferable and it may be that avoidance of planar obstacles at a comfortable walk is within the capabilities of the three groups tested and regardless of the degree of difficulty, the task may not have had enough context specificity to dance or athletic training to elicit any behavioural differences. Higuchi et al. (2001) found differences between American football players and the control athletes (i.e. varsity athlete that are not required to pass through small apertures during practice or play) during aperture crossing only once the participants increased their speed of passing through from walking to running.

The lack of differences between the dance trained in the current study and the non-athletes may be due to the breadth of dance styles that the participants were trained in. The individuals tested, while ballet was part of their training, were not constrained to a single type of dance. In much of the literature discussed in the introduction dancer trained in ballet were tested. It was thought that since the task of crossing from a start to an end goal at a comfortable self-selected pace in the current study was similar to the work by Panchuck and Vickers (2011) that differences in gait speed and possible resulting avoidance behaviour would be observed. The “crossing” segment in the Panchuck and Vickers (2011) study had free foot placement and two condition requiring placement within a given path (wide or narrow); the elite ballet dancers performed the task of crossing at a significantly higher pace than the non-dancers. The current study found no such inherent propensity of dancers to select a faster pace when walking to the goal. As the ballet dancers were recruited from a professional dance company (Alberta Ballet) in the Panchuck and Vickers (2011) study and the current investigation recruited from the varsity dance team at Wilfrid Laurier University, it is likely the stringency of dance inclusion criteria that would have to be change to tease out training effects compared to non-athletes during obstacle avoidance.

Thus, further directions to exploit various attributes of specialized populations such as dancers or field athletes may require the addition of timed performance during planar obstacle avoidance (i.e. have the participants reach the goal in varying time increments while avoiding the planar obstacles). Decreasing the time allotted to reach the goal may elicit differences from an untrained control group but it may be hard to differentiate whether they are due to physical, perceptual, or cognitive attribute (or a combination there of). Increasing the cognitive demand through dual tasking could be another possible direction to investigate in the future, as expert athletes should also be superior in their balance control during increased cognitive load compared to novice or non-athletes (Abernathy et al., 1994; Ackerman, 1988).

Single vs. Double Obstacle Avoidance

As previously mentioned, all participants were able to successfully avoid the planar obstacles presented. Previous literature, exhibited preferred foot placement for medial or lateral stepping preference well above chance (considering the number possible alternate foot placement selection categories relative to the obstacle were between 4 and 8), ranging from 53-95% of trials, when the medial-lateral displacement of the alternate foot placement is smaller than the required adjustments in the anterior-posterior direction

(Patla et al., 1999; Moraes et al., 2004; Moraes et al., 2007). In the current study, participants were found to adhere to their medial avoidance preference for 100% of the single obstacle trials.

It was expected that the addition of a secondary obstacle would increase the challenge to dynamic stability and thus result in an avoidance strategy that would allow for the maintenance or widening of the base of support (i.e. Medial-Lateral (ML) or Lateral-Medial (LM) alternate foot placement). LM selection was rarely the dominant avoidance chosen and if so, the preference was not maintained when the appearance was delayed (for individual avoidance behaviour see Appendix). Nearly half of the 33 participants maintained a preference for Medial-Medial (MM) regardless of the double obstacle condition (n=16), a behaviour that likely exploits the forward momentum of the center of mass (COM) and maintains foot placement along the locomotor axis. This appeared to manifest in the analysis of the minimum Dynamic Stability Margin (DSM) two steps before the first obstacle (i.e. N-2) where significant differences were found between MM, ML, and LM avoidances.

Moraes and Patla (2006) calculated a margin of dynamic stability (MDS) (based upon the distance of the extrapolated COM position and the maximum reach of the center of pressure, as they had collected forceplate and kinematic data) from the step preceding the obstacle, the avoidance step, and the step following avoidance. While they did not discuss this measure in relation to stability or forward momentum it should be noted that they found similar differences between medial and lateral alternate foot placement, where the margin was larger in the preceding step (i.e. N-1) during lateral avoidance compared to medial (~8 cm and ~5 cm, respectively). The analysis done in 'Treating Each Trial as Independent' for the minimum DSM at N-2 during the double obstacle condition for the current study found that MM and LM had analogous margins to those calculated by Moraes and Patla (2006) (MM: 5.4 cm; LM: 9.7 cm) where the resulting avoidance step at the first obstacle (N) was lateral for the greater difference between the COM and outer border of support. It would appear that when introducing a second subsequent obstacle that the primary step dictating the behaviour occurs two steps before the first obstacle. This difference between the Moraes and Patla (2006) work and the double obstacles conditions of the current study is corroborated by the work of Matthis and Fajen (2013a, 2013b) where they argued that simple avoidance can be accomplished efficiently with one step worth of visual information but when the complexity of the task is increased then at least two preceding step lengths of visual information is needed.

During single obstacle avoidance foot placement could have been made in either the medial or lateral direction; we have discussed the MM and LM avoidance observed when a second obstacle was introduced, a third avoidance strategy of Medial-Lateral (ML) foot placement was observed. A small proportion of participants (n=4) selected ML avoidance consistently for all trials. The minimum DSM at N-2 was significantly smaller for this alternate foot placement strategy compared to MM or LM. This may suggest that in addition to the avoidance at the first obstacle being dictated at N-2, that the stability margin determines the avoidance at the subsequent obstacle.

Influence of Delaying the Appearance: the double obstacle condition

The contribution of gait parameters encompassing N-2 and the area prior to that in the ability to predict the resulting avoidance strategy suggests that the two steps before the obstacles are minimum needed for success. The main influence of preceding visual information about the undesirable landing spot (at a distance or at N-2) on these dictating parameters were identified by controlling for behaviour (MM). The influence of double obstacle appearance on foot placement in the medial-lateral direction at N-2 is incongruent with previous findings; Moraes, Lewis, and Patla (2004) found participants parsed out their adjustments to foot placement during the preceding three steps congruent with the direction of their “planned” avoidance. The preferential direction of the alternate foot placement was maintained when Moraes et al. (2004) introduced a spatial constraint (i.e. target for foot placement) in the step before the obstacle. Whether the individual was able to adapt their locomotor pattern to allow for avoidance early on or from the step before the obstacle the observed direction of avoidance satisfied minimum displacement from footfall during straight walk through conditions. In contrast, the current study found the medial-lateral foot placement tended away from the direction of avoidance (i.e. the avoidance step was medial to the obstacle but the footfall at N-2 was lateral or outside of normal position during straight walk through) during the double obstacle conditions and that this disparity between the foot placement at N-2 and avoidance direction was exacerbated when the obstacle was presented early in the trial (as steady state locomotion was reached). In that regard the findings were similar to those found by Moraes et al. (2004) where the shift in foot placement occurred with out any appreciable change in the manner that individuals avoided the obstacles. Individuals that preferred a single avoidance strategy, MM or ML, exhibited this significant shift in the medial-lateral foot placement farther from the midline when the obstacles were presented early during the walk to the goal was found within . While MM steppers compose the majority of participants when analyzed with the ML steppers (recall MM were separately analyzed on their own in ‘Medial-Medial Avoidance: controlling for behaviour) the main effect of temporal obstacle appearance was shifted slightly farther from the midline than for MM alone but the direction and relative degree between the timing of appearance was maintained. It was first suggested by Moraes et al. (2004) that while minimal displacement of the foot from the natural landing position during straight walking is important, it is not the primary factor dictating the selection of alternate foot placement and the foot placement at N-2 during the double obstacle conditons of the current study (when individuals were required to navigate about a more complex terrain) bolsters this postulation.

In the current study a large proportion of individuals had significant differences in certain measures across the different timings of appearance for the double obstacle projection while exhibiting no change in the alternate foot placement strategy they selected. It would appear that the individuals did not substantially alter their gait pattern whether given two or more than two steps to implement the avoidance of the paired obstacles. These findings seem in accordance with the premise that locomotion is controlled in feed forward manner and visual information becomes important for the adjustment of the locomotor pattern to successfully avoid undesirable footholds in the leading two steps before. In the works by Matthis and Fajen (2013b) the successful navigation of a complex terrain appears to reach ceiling between 2 and 2.5 step lengths of visual information of the upcoming environment; it would appear that this ceiling effect is mirrored by the lack of influence delaying the appearance of the double obstacle condition had on the selected avoidance behaviour.

Medial-Medial vs. Medial-Lateral Avoidance

Two of the three possible strategies during double obstacle avoidance was found to be consistently preferred by some individuals, regardless of when the obstacles were presented. The majority chose MM (n= 16) but a small proportion held a preference for ML (n= 4). In regards to the determinants proposed by Patla et al. (1999), MM is an avoidance strategy that values forward progression as it would deviate the least from the locomotor axis. Those that chose to step ML placed their initial avoidance step along their locomotor axis and then step lateral to the obstacle which would allow the return to the natural width of the base of support or if the first avoidance was greatly destabilizing then the base could be extended farther out; this alternate foot placement strategy in contrast to MM would be less dependent of the conservation of forward momentum and favour stability instead.

An ANOVA comparing the two groups revealed an influence of the minimum DSM at N-2 for significantly discriminating between MM and ML preference. The COM travelled much closer (~ 5 cm) to the outer border of the foot during ML avoidance than MM. When considering these values along with the relative medial-lateral foot placement this would place the COM traveling along the centre of the path from the start to the goal for those that selected to make a MM avoidance. It is put forward here that this medial-lateral position of the COM relative to the direction of forward momentum coincides with the assumption made in the previous literature on alternate foot placement (i.e. Patla et al., 1999; Moraes et al., 2004; Moraes et al., 2007) that medial selection is a resultant of optimizing the forward progression during avoidance. Those that consistently chose to step in a ML fashion allowed a narrower minimum DSM to occur; this may have affected the individuals capabilities of remaining stable while continuing along in their forward trajectory in the secondary avoidance step. Based upon these rudimentary findings, the measure of dynamic stability may allude to the value of stability in dictating avoidance and warrant further investigation.

Variable Avoidance Behaviour

As the observed alternate foot placements were categorized into MM, ML, or LM avoidance and the current study used a repeated measures design, averaging the gait parameters would not provide a true picture of those individuals that selected a combination of these avoidances across the trials. The coefficient of unalikeability was used to give a value representative of the differences in the various participants as to how consistent they were in their preference (or lack there of) in selecting an avoidance strategy. Unalikeability focuses on the proportion of possible comparisons which are unalike but not any indication as to the specific distribution of preference across the possible behaviours. For both double obstacle conditions (steady state and delayed appearance) a significant positive relationship was found with the minimum DSM at N-1, where an increase in the variability of the minimum DSM paralleled an increase in the variability of the alternate foot placement. When the avoidance selection was compared between those that had no variability in their avoidance strategy (i.e. MM vs ML) minimum DSM at N-1 was significantly different between the two. Thus, it can be inferred that the correlational relationships observed are likely due to the inclusion of variability due to variable selection and/or the how different the LM avoidance is (and its determining gait parameters) from the other two strategies.

Treating Each Observation as Independent

The rational for treating each observation as independent as a means of inferring the relationship of double obstacle avoidance selection for all three possible choices and the proposed gait measures was based upon that while an individual may be more or less variable across trials that it is the gait parameters during each specific trial that truly governs the avoidance selection. It was previously discussed that there was a negligible effect of the temporal presentation of the double obstacle conditions, between steady state and N-2 appearance, on the selection of the alternate foot placement strategy. This assumption held true for the majority of the tested parameters excepting the minimum DSM at N-1 which revealed an interaction effect regarding the timing of appearance and the avoidance selected; Lateral-Medial (LM) avoidance appears to have this margin affected the most by delaying the appearance within the given avoidance behaviours.

It may viewed that by N-1 the avoidance strategy may already be determined as minimum DSM at N-2, approach velocity and ML COM variability, calculated from when the obstacle became visible (~3.7 before origin) to N-2, in summation can predict (from the observed pairwise comparisons) which of the three avoidance strategies is implemented. When a LM avoidance resulted, the individual was traveling at a significantly slower speed than those that stepped medially at the first obstacle. Recall, that when discussing the effects of athletic training in previous literature that moving through space at a greater speed with no cost to the success and/or accuracy of navigation was suggested to be indicative of populations that value forward momentum (Gerin-Lajoie et al., 2007; Panchuck & Vickers, 2011). It would appear that for the group of young female adults tested that those that moved slower were more conservative, widening their base of support at N. It is also interesting to note that none of those trained in dance selected to avoid the obstacle in a LM manner. The large value of minimum DSM at N-2 and low variability of the COM in the frontal plane may also be indicative of anticipatory postural adjustments (APAs) being made to complete the LM avoidance selection successfully and would address why this margin becomes even larger during single support at N-1, specifically during steady state appearance where there is a greater opportunity to implement an APA.

From the pairwise comparisons of ML COM variability and minimum DSM at N-2 it would appear that MM and LM avoidance are more similar to each other than they are to ML. Where ML had the highest ML COM variability but the smallest minimum DSM at N-2; MM falls in the middle and LM on the other end of the spectrum with the lowest ML COM variability but the largest difference at the minima between the COM and the anterior ankle. Where the analysis comparing those that had no within subject variability of alternate foot placement selection for MM and ML avoidance indicated that minimum DSM at N-2 was impactful in determining the behaviour and in turn suggested that larger margin allowed for the COM to travel along the locomotor axis. When the variable trials are added to analysis we see an emergence in the effect of foot placement at N-2 in addition to the minimum DSM at N-2 and ML COM variability between MM and ML avoidances. When considering the minimum DSM and the foot placement are calculated using the medial-lateral position of the anterior ankle marker, the location of the COM relative to the locomotor axis appears to be similar (i.e. for ML avoidance the foot placement is at about -7 cm with a margin of 2 cm and MM has an average foot placement at around -10 with a margin of about 5 cm; both result in a difference of -5 cm at N-2). These additional observations included into the statistical analysis lends well to the argument of the first avoidance step falling at a position the optimizes forward momentum and the larger variability of the COM in the medial-lateral direction during ML selection suggests the ability to stabilize the COM in the frontal plane dictate whether foot placement along the axis of locomotion can be maintained during the avoidance of the secondary obstacle.

Conclusion

The double obstacle conditions became the pinnacle of the experimental manipulations done in the current study in regards to the insight gain on how various gait parameter dictate alternate foot placement. The supposition that visual information is of the most importance in the preceding two step length when adapting locomotion in response to complex terrain was substantiated by the lack of influence delaying the appearance of the planar obstacles had upon the resulting alternate foot placement selection.

The ability of individuals to gradually affect changes to the gait pattern to avoid the obstacles during steady state appearance gave contrary evidence for the minimization of displacement from the natural foot placement as a determinant (as proposed by Patla et al., 1999). During LM avoidance there appears to be evidence of anticipatory postural adjustment being made when the obstacles are presented early on, a seemingly conservative behaviour that would suggest the LM stepping about the obstacles favours stability over forward momentum. Medial-lateral foot placement at N-2 collectively with minimum DSM and medial-lateral COM variability does appear to differentiate those that are able to maintain forward momentum (MM) after initially stepping medially to the first obstacle of the two from those who may require a more ‘stable’ foothold at the second obstacle (ML).

In future, the addition of timed walking or varying self-selected fast, comfortable, and slow paces (i.e. have the participants reach the goal in varying time increments while avoiding the planar obstacles) may provide further insight as the current found that trials when individuals selected to step LM had approached the obstacles at a significantly slower rate. While the current task did not appear to have enough task specificity to elicit any group differences from the young adult females tested a shift to testing those with degradation to their perception-action capabilities (e.g. older adults, young adults with visual impairments, traversing a compliant surface, etc.) would build upon the rational of using agent capabilities to pin-point integral gait parameters dictating the alternate foot placement.

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Appendix

Health History Questionnaire

Participant:___________________ M/F Date:_________________

D.O.B.:________________(mm/dd/yyyy) Team/Position:_____________________

1. At what age did you begin playing organized sport?______

2. How many years have you played?___

3. Do you wear a mouth guard while playing? __yes __no
If yes, what kind?
___stock ___boil & bite
___custom, front teeth ___custom, all

4. Have you ever suffered from neck pain within the past 6 months? __yes __no

5. Have you ever suffered a concussion?
__yes __no __not sure

6. If yes to #5,
a) How many times while playing sport in the past 6 months?___
b) Date of last concussion?___________
c) How long did the symptoms last (for last concussion)?
__ 1-3 days __4-7 days __8-10 days
__ 11-14 days __more than 2 weeks
c) Who told you that you could not play because of the last concussion?(select all that apply)
__myself __coach __team therapist
__family doctor __chiropractor __other
d) After the last concussion, how long did you refrain from physical activity?
__ 4-7 days __8-10 days __11-14 days
__ 15-21 days __more than 3 weeks

7. Have you ever been knocked unconscious? __yes __no

8. If yes to #7,
a) How many times in the past 6 months? _____
b) What is the longest duration you've been knocked unconscious? ________

9. In the past 6 months, after being hit in the head in sports, have you experienced any of the following symptoms:
__ confusion __ getting 'dinged'
__ headaches __ balance problem
__ nausea __ getting 'bell rung'
__ dizziness __ ringing in the ears
__ blurry vision __ poor memory
__ other:___________________

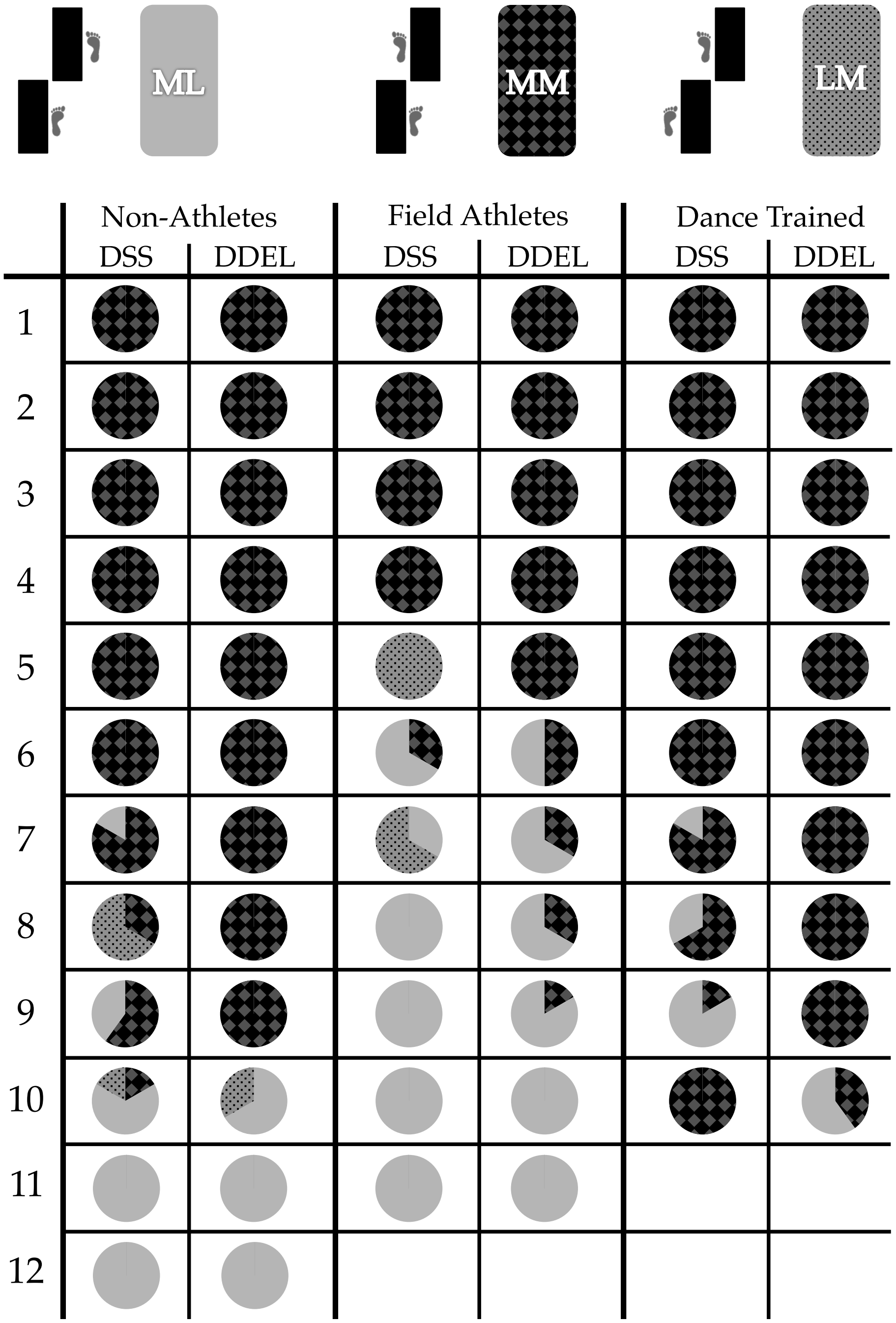
10. In regards to how you feel NOW, please rate the following:

	none	mild		moderate		severe	
headache	0	1	2	3	4	5	6
"pressure in head"	0	1	2	3	4	5	6
neck pain	0	1	2	3	4	5	6
nausea/vomiting	0	1	2	3	4	5	6
dizziness	0	1	2	3	4	5	6
blurred vision	0	1	2	3	4	5	6
balance problems	0	1	2	3	4	5	6
sensitivity to light	0	1	2	3	4	5	6
sensitivity to noise	0	1	2	3	4	5	6
feeling slowed down	0	1	2	3	4	5	6
"don't feel right"	0	1	2	3	4	5	6
hard to concentrate	0	1	2	3	4	5	6
feeling "in a fog"	0	1	2	3	4	5	6
difficulty remembering	0	1	2	3	4	5	6
fatigue/low energy	0	1	2	3	4	5	6
confusion	0	1	2	3	4	5	6
drowsiness	0	1	2	3	4	5	6
trouble falling asleep	0	1	2	3	4	5	6
more emotional	0	1	2	3	4	5	6
irritability	0	1	2	3	4	5	6
sadness	0	1	2	3	4	5	6
nervous/anxious	0	1	2	3	4	5	6

11. Do the above symptoms get worse with physical activity? __yes __no

12. Do the above symptoms get worse with mental activity? __yes __no

Double obstacle avoidance strategies (ML, MM, and LM) proportions selected by individual participants during the two different timings of appearance (i.e. during steady state (DSS) and delayed until N-2 (DDEL); individuals separated into their training groups (Non-Athletes, n= 12; Field Athletes, n= 11; Dance Trained, n= 10)



Visual summary table of the result sections: *MM Avoidance controlling of variability* (dashed lines), *MM vs ML Avoidance* (dotted lines), *correlation of Variable Avoidance Behaviour* (circles), and *Treating Each Trial as Independent* (pairwise comparisons in solid lines; painted strokes represent interaction). Proposed gait parameter colour scheme: approach velocity (purple), ML COM variability (blue), ML FP at N-2 (green), minimum DSM at N-2 (red), and minimum DSM at N-1 (orange).