# DETERMINANTS AND STRATEGIES FOR THE ALTERNATE FOOT PLACEMENT

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

**Abstract**

Undesirable landing area (e.g., a hole, a fragment of glass, a water puddle, etc) creates the necessity for an alternate foot placement planning and execution. Previous study has proposed that three determinants are used by the central nervous system (CNS) for planning an alternate foot placement: minimum foot displacement, stability and maintenance of forward progression. However, validation of these determinants is lacking. Therefore, the general purpose of the series of studies presented here is to validate and test the generality of the decision algorithm of alternate foot placement selection developed previously. The first study was designed to validate the use of a virtual planar obstacle paradigm and the economy assumption behind minimum foot displacement determinant. Participants performed two blocks of trials. In one block, they were instructed to avoid stepping in a virtual planar obstacle projected in the screen of a LCD monitor embedded in the ground. In another block, they were instructed to avoid stepping in a real hole present in walkway. Behavioral response was unaffected by the presence of a real hole. In addition, it was suggested that minimum foot displacement results in minimum changes in EMG activity which validates the economy determinant. The second study was proposed to validate the stability determinant. Participants performed an avoidance task under two conditions: free and forced. In the free condition participants freely chose where to land in order to avoid stepping in a virtual obstacle. In the forced condition, a green arrow was projected over the obstacle indicating the direction of the alternate foot placement. The data from the free condition was used to determine the preferred alternate foot placement whereas the data from the forced condition was used to assess whole body stability. It was found that long and lateral foot placements are preferred because they result in a more stable behavior. The third study was designed to validate the alternate foot placement model in a more complex terrain. Participants were required to avoid stepping in two virtual planar obstacles placed in sequence. It was found that participants used the strategy of planning the avoidance movement globally and additional determinants were used. One of the additional determinants was implementation feasibility. In the third study, gaze behavior was also monitored and two behaviors emerged from this data. One sub-group of participants fixated on the area stepped during adaptive step, whereas another sub-group anchor their gaze in a spot ahead of the area-to-be avoided and used peripheral vision for controlling foot landing. In summary, this thesis validates the three determinants for the alternate foot placement planning model and extends the previous model to more complex terrains.

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# Chapter 1

# Introduction

Unobstructed gait has been extensively studied in the last decades. Winter (1991), for instance, has catalogued detailed descriptions of walking under these stable conditions and provided a good understanding of the principles of organization in locomotion control. For example, it was found that knee and hip moments-of-force covary to maintain vertical support against gravity and trunk stability (Winter 1987). However, normal daily activities require the locomotor control system to complete more demanding tasks than straight-path and unobstructed walking. In order to further understand the dynamics of control, it is necessary to examine the transitory changes in locomotor behavior. Changes in locomotion direction (Patla et al. 1991, Hollands et al. 2002; Fajen and Warren 2003), increase in ground clearance to adapt gait pattern when stepping over obstacles (Patla et al. 1991; Patla and Rietdyk 1993; Austin et al. 1999), step length modulation (Lee et al. 1982; Warren et al. 1986; Patla et al. 1989a, 1989b), and alternate foot placement when avoiding an undesirable area on the ground (Patla et al. 1999; Moraes et al. 2004) are typical strategies used to maintain locomotion in a cluttered terrain. These tasks are referred to as locomotor adaptive strategies. The study of adaptive locomotion allows us to understand how locomotor output is modulated to meet the demands of the environment and how locomotion is controlled. Adaptive locomotion allows us identifying the main factors that affect locomotion planning and execution.

**Visual control of adaptive locomotion**

Vision is the most adequate sensory system to guide locomotion since it provides information about animate and inanimate features at a distance. Vision provides exteroceptive information that is used to locate objects in the external environment relative to one another. It also provides exproprioceptive information about the position and movement of a part of the body relative to the external environment (Patla 1997).

The contribution of vision to locomotion has been the focus of several studies in the motor control field. In essence, two major aspects have been addressed: the nature of visual information, and how visual information is acquired during locomotion (Patla 1991). The nature of visual information is associated with mechanisms of relevant information extraction from the environment such as surface characteristics, terrain layout, and obstacle characteristics. For instance, disruption in the terrain layout provided by the optic array indicates the presence of an obstacle (Gibson 1958). Patla and Vickers (1997) have shown that individuals do not fixate on the obstacle when stepping over it or even one step before they encounter it. Gaze is fixated on the obstacle during the approach phase and it is alternated with travel gaze fixations, which is a gaze behavior where the gaze moves along at the same speed of locomotion. Furthermore, visually inferred information such as compliance or frictional characteristics of a surface is important in determining an undesirable landing area (Patla 1991). The acquisition of visual information is related to the spatio-temporal characteristics of visual sampling (Patla et al. 1996). Different studies have shown that environmental sampling is not continuous; but rather, it is intermittent (Patla et al. 1996; Patla 1991, 1997; Thomson 1980). The importance of intermittent sampling is illustrated by the fact that we are able to walk and see the surrounding scenery at the same time. Patla et al. (1996) have shown that the total duration of visual samples of the environment varied from 10% (no obstacle or foot placement requirement in the pathway) to 40% (presence of a hole in the pathway) of the movement time which was similar in both conditions. In addition, step length and width modifications do not affect the number or duration of visual samples (Patla et al. 1996).

One of the first studies that has addressed the issue of visual control of adaptive locomotion is the work done by Lee et al. (1982). They were the first to identify the visual regulation of step length when performing a locomotor task which required great accuracy (i.e., hitting takeoff board in long jumping). They found an increase in the toe-board distance variability from the beginning to a few steps before the take-off board (stereotyped-based mode of control) which was followed by a decrease in the variability (visually-based mode of control) culminating with a very small variability at the take-off step. Variability reduction was considered the result of visually adjusting the length of the final steps in order to zero-in on the board. This assumption is based on the idea that absence of visual information would result in a consistent increase in foot placement variability. In fact, absence of accurate foot placement requirement during unobstructed straight line walking results in a constant increase in foot placement variability (Moraes et al. 2004) as well as removal of the take-off board during the triple jump (Maraj 1999). Several studies have followed the seminal work of Lee et al. (1982) and have pointed out the consistent pattern of foot placement variability during the approach phase of long jumping (Berg et al. 1994; Hay 1988; Hay and Koh 1988; Maraj et al. 1998; Montagne et al. 2000; Scott et al. 1997) and walking to a target (Moraes et al. 2004), indicating a switch from a stereotyped- to a visually-based mode of control during the approach phase. The first phase is directed towards reaching an optimal running speed, whereas the second allows step length to be adjusted to zero-in on the board. More recently, Montagne and his group (Montagne et al. 2000; de Rugy et al. 2000) have suggested a perception-action coupling mechanism of control where, only when necessary, adjustments are performed. In support of continuous visual control, a significant relationship between the total adjustment needed and the step number of the adjustment initiation was found indicating that greater amount of adjustment results in earlier regulation of foot placement. They argue that the control system has a tolerance level, and step length is only modified when the amount of regulation exceeds the tolerance level.

**Focus of present study: alternate foot placement selection**

Previous work on step length and width modulation has focused on movement implementation when the task was specified either by external cues or was defined *a priori*. Changes in step length and width are essential for adapting locomotion to uneven terrain and these are the mechanisms available to the control system to avoid stepping in undesirable locations. These changes in step length and/or width with the intention of avoiding an undesirable area are termed alternate foot placement. The present study will focus on gait adaptations that involve avoiding stepping in undesirable locations. More specifically, the parameters involved in selecting/planning alternate foot placement will be investigated.

An undesirable landing area (e.g., a hole, a fragment of glass, a water puddle, etc) creates the necessity for alternate foot placement selection, planning and execution. Only recently alternate foot placement has begun to be studied and it was found that selection of alternate foot placement is not random, but systematic (Patla et al. 1999). For the same obstacle shape and size, different dominant choices were found based on where the obstacle was positioned in relation to the normal landing position of the foot. It was proposed that alternate foot placement is not solely sensory-driven, since visual information by itself is not enough to decide where to land (Patla et al. 1999; Moraes et al. 2004). It was originally proposed by Patla et al. (1999) that visual and proprioceptive inputs, and a set of internal rules containing three determinants are used to select the appropriate output (Figure 1). Sensory information is used to identify the obstacle area and to provide a prediction of the normal foot placement if no change in step length and width are made. Visual information provides information about the location of the obstacle area (Patla 1991, 1997), whereas the interaction between vision and proprioception is used to estimate normal foot placement. This prediction of future normal foot placement is used to compute the amount of foot displacement required for each alternate foot placement option: lengthening (long), shortening (short), narrowing (medial), and widening (lateral) the step. This computation is necessary to identify which option minimizes foot displacement. Minimum foot displacement is one of the determinants used by the control system to select alternate foot placement, according to Patla et al. (1999) and Moraes et al. (2004). They have shown that people prefer alternate foot placements that minimize foot displacement. In general, it was found that if only one option satisfies the minimum foot displacement determinant, that option is the preferred one, although there seem to exist some exceptions that will be described later. It is assumed that minimizing foot displacement is desirable because it would generate an economical movement. Patla et al. (1999) have proposed that minimum foot displacement would minimize changes in ongoing muscle activity, which in turn would increase movement economy. Different studies have proposed that economy is an important parameter in movement planning/execution based on an evolutionary perspective (Alexander 2002; Patla and Sparrow 2000).

Psychophysical studies have shown that the integration of visual and proprioceptive information is critical for estimating speed and path distance. Using virtual reality, Sun et al. (2003, 2004) have been able to decouple optic flow and proprioceptive information by altering the optic flow gain (OFG) projected on a head-mounted display apparatus while pedaling a stationary bicycle. Sun et al. (2003) found that decoupling of optic flow and proprioception affects speed estimation during self-motion, suggesting that both sensory systems are essential for proper speed estimation. In another study Sun et al. (2004) have studied the relative contributions of optic flow information and proprioceptive information in estimating a relative path length. Removal of proprioceptive information made the estimation errors greater, especially at the extremes of the stimulus scale. Therefore, availability of proprioceptive information increased accuracy of relative path length estimation, even though proprioceptive information was inconsistent with visual information. It demonstrates that active movement (locomotion) facilitates visual perception of path length traveled as predicted by Gibson (1958).

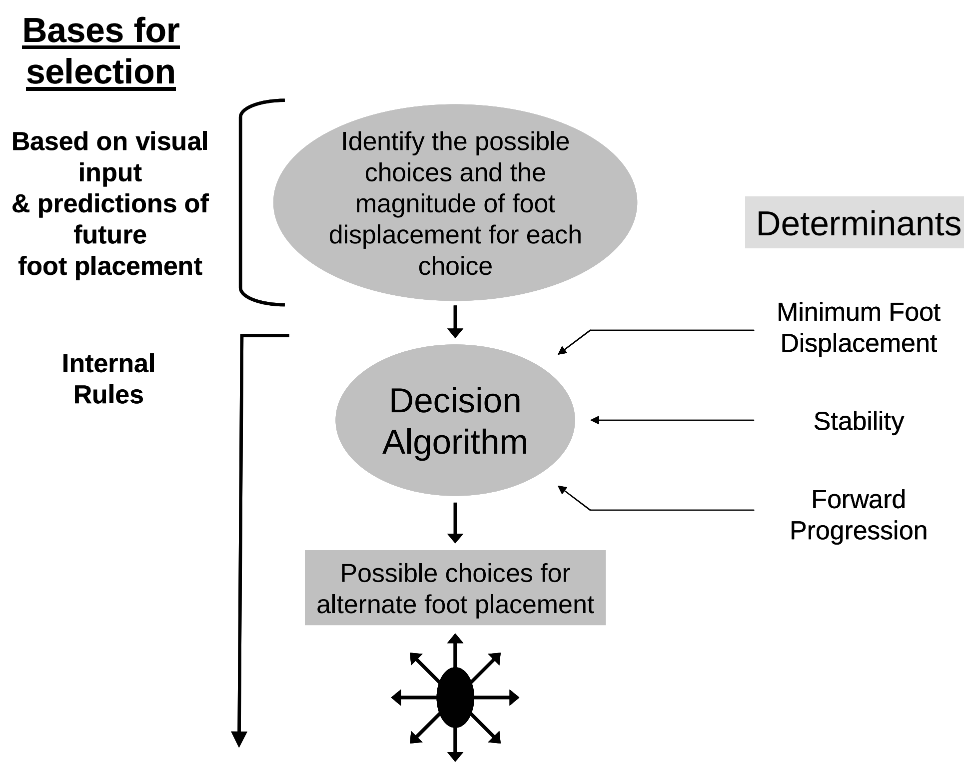


*Figure 1.* Alternate foot placement model showing the bases for selection and the main determinants.

A recent approach that has emerged as a theoretical reason for the prediction ability of the control system is the concept of forward internal model (Haggard 2001). The forward internal model predicts the future state of the motor apparatus based on the efferent copy of motor commands, sensory inputs about the current state of the motor system, and a learning mechanism to ensure that the forward model accurately reflects the motor system behavior and adapts over a long time scale to its changes (Haggard 2001; Miall 1998; Wolpert et al. 1998). Its output is a sensory prediction that estimates the sensory consequences of the motor commands. Therefore, prediction of the future normal foot placement position may be the output of an internal model based on visual and proprioceptive information of the movement as well as an efferent copy of the locomotor control system.

The presence of more than one option minimizing foot displacement requires additional determinants. The other two determinants are stability and maintenance of forward progression (Patla et al. 1999; Moraes et al. 2004). When minimum foot displacement is similar for both options in the same plane of motion (i.e., sagittal or frontal), long and medial choices are preferred over short and lateral choices, respectively. It was proposed that these preferences were stability based since short adjustments could result in unstable movements due to the need for reducing forward momentum. If not properly controlled, this forward momentum reduction could generate an angular momentum that ultimately would lead to a fall. Medial adjustments were preferred because they would minimize mediolateral center of mass (COM) acceleration due to reduction of the distance between COM and center of pressure (COP) as proposed by the inverted pendulum model (Winter 1995). Maintenance of forward progression was shown to be important by the preference for making changes in the plane of progression. When minimum foot displacement was the same for one option in the sagittal plane and another option in the frontal plane, change in the sagittal plane or plane of progression was preferred.

Although Patla et al. (1999) have proposed that minimum foot displacement was the major determinant guiding selection of alternate foot placement, they were unable to provide quantitative evidence that would substantiate this. The first quantitative evidence for minimum foot displacement was provided by Moraes et al. (2004). They measured the amount of foot displacement for each choice and computed the predicted minimum foot displacement for each option based on foot length/width and average foot placement position during normal walking. They found that for most of the planar obstacles tested the dominant choice was the one that resulted in minimum foot displacement. In addition, they have shown that minimum foot displacement is not the main factor guiding the selection of alternate foot displacement as advocated by Patla et al. (1999). For two of the obstacle positions, minimum foot displacement was either medial or lateral and the dominant choice was long. Therefore, alternate foot placement choice is a result of finding the solution that satisfies all three determinants together.

When the response had to be selected and implemented under a time constraint, as in Patla et al.'s (1999) study (i.e., within one step), the determinants were satisfied in the following order: minimum foot displacement, stability, and forward progression. Not all the determinants were satisfied in all cases when the foot placement had to be altered quickly. For example, in those conditions when the participants chose to step medially (Patla et al. 1999), they satisfied the first two determinants, but not the last. In contrast, when there are no time constraints (obstacle is seen from the starting point) in response planning and implementation as in Moraes et al.'s (2004) study, the priority shifts. Forward progression becomes the first determinant, followed by stability, and lastly minimum foot displacement. Maintenance of forward progression priority is illustrated by the bias toward stepping long-medial when the medial choice is more economical as in one of the obstacle positions tested. This is understandable, since when adequate time for planning and implementing alternate foot placement is available, deviations from the end-point goal can be minimized through proactive control during the approach phase.

Since alternate foot placement implementation basically involves step length/width regulation, studies related to control mechanisms of step modulation will be reviewed. Lee et al. (1982) proposed that step length changes were achieved by modulating vertical impulse during the visually controlled phase since they found a significant correlation between flight time and stride length. In addition, they proposed that runners used time-to-contact (i.e., tau) relative to the board to control gait based on the finding that jumpers adjusted a time parameter (i.e., flight time) instead of a space parameter during the approach phase. Warren et al. (1986) have provided additional support for this notion by requesting participants to step on targets unevenly spaced on the ground. They found the adjustments in step length were a consequence of modulating the vertical component of impulse applied during the stance phase. Furthermore, they suggested the tau gap (i.e., the difference of the tau values for two approaching targets) was used to define vertical impulse that would equalize step time to tau gap.

Patla et al. (1989a) have expanded on the work by Lee et al. (1982) and Warren et al. (1986) by directly measuring the kinetics of step length regulation. They found that not only vertical impulse, but also horizontal impulse was regulated to achieve the task demand of shortening or lengthening the step. The larger contribution came from vertical impulse as postulated by Warren et al. (1986), but a significant contribution was also provided by the horizontal impulse component. Patla et al. (1989a) have also shown that there is not a single strategy to regulate step length. Participants were faced with early or late visual information cueing step adjustment (i.e., shortening or lengthening). Results indicated that the mechanisms used to lengthen the step in the early cue condition were different from the late cue condition. In the early condition, the horizontal braking impulse was reduced, whereas in the late condition the horizontal push-off impulse was increased. It was suggested that the simple mechanism presented by Lee et al. (1982) and expanded by Warren et al. (1986) is not entirely adequate. The results from Patla et al. (1989a) suggest a complex task-specific modulation of locomotion to alter step length.

Modifications in step length and width can be implemented within one step cycle (Patla 1991). Step length and width regulation are the strategies available to the central nervous system (CNS) to implement an alternate foot placement. The percentage of step width regulation is high only for small changes (i.e., 30°) when a visual cue is provided at contra-lateral heel contact (CHC). Therefore, there is a limitation on the magnitude of step width modulation that can be implemented within one step, probably due to weakness of the muscles responsible for implementing the modification (Patla et al. 1991; Patla 1991). Step width regulation is achieved by increasing the anterior-posterior (AP) and vertical braking impulse in order to reduce the forward velocity and by modulating the medial-lateral (ML) component accordingly. In addition, Patla (1991) found an increase in gluteus medius from narrow to wide (60°) steps during early swing phase.

Step length regulation is high when a visual cue is provided at CHC, and it is independent of the amount of adjustment (+50% and -50%) (Patla 1991). Changes in muscle activity of the ipsi-lateral limb when lengthening the step fall into three major functional categories: push-off action (late stance), pull-off (early swing), and limb deceleration (late swing). The increase in soleus activity during late stance makes the push-off more vigorous. The increase in biceps femoris activity at late stance increases knee flexion during early swing and this facilitates hip flexion by reducing the moment of inertia around the hip joint. During early swing there is an increase in rectus femoris activity in order to compensate for the biceps femoris action during late stance. This will ensure adequate knee extension at the end of swing phase. During late swing, biceps femoris activity is reduced allowing greater knee extension. An increase in soleus activity was also observed during late swing in order to adjust foot angle for appropriate landing (Patla 1991).

**Movement planning based on multiple factors**

Movement selection and planning is one of the main topics of research in motor control and one of the main goals is to understand how a specific movement is adopted when more than one option allows a goal to be achieved. Recent models of upper limb movements have considered multiple factors when planning a movement (Rosenbaum et al. 2001a, 2001b; Patla and Sparrow 2000) instead of only one (Uno et al. 1989). Rosenbaum et al. (2001a) have proposed a model for manual prehension where the end-posture is selected before movement execution and is based mainly on the notion of a constraint hierarchy. Constraint hierarchy is defined as a list of prioritized factors necessary to perform the task. For example, in a simple reaching task, accuracy (hand-target proximity at the time of movement completion) and movement efficiency (expend little energy) are the constraints considered. The presence of an obstacle and the intention of avoiding it adds a new constraint (i.e., do not collide with the obstacle). The constraints are then considered in a different order: 1) accuracy, 2) hand/arm distance from an obstacle, and 3) efficiency. Hence, additional constraints redefine the task and weights the priorities differently (i.e., efficiency is less important when avoiding the obstacle). This is consistent with the findings of Moraes et al. (2004) who have shown that response time constraint affects the priorities placed on satisfying various determinants in the choice of alternate foot placement.

**How can alternate foot placement determinants be validated?**

Both studies presented previously, related to alternate foot placement, have not validated two of the determinants (Patla et al. 1999; Moraes et al. 2004). Moraes et al. (2004) have provided validation for the minimum foot displacement determinant, but the economy assumption behind this determinant is lacking validation. In addition, the generality of these determinants in guiding alternate foot placement in more complex terrains needs to be tested. Therefore, the general purpose of the series of studies presented here is to understand how people select, plan, and implement alternate foot placements. More specifically, the studies presented here were designed to validate and test the generality of the determinants for selecting alternate foot placement proposed by Patla et al. (1999) and expanded on by Moraes et al. (2004). In the next sections, each of the determinants will be discussed, and validation mechanisms will be briefly presented.

**Economy assumption for the minimum foot displacement determinant**

One of the determinants used for selecting alternate foot placement is minimum foot displacement. Minimum foot displacement would require minimum changes in the ongoing muscle activity and therefore would increase economy (Patla et al. 1999). It was shown by Patla et al. (1999) and Moraes et al. (2004) that the dominant choice coincided with the option that minimized foot displacement. Since in normal walking, the preferred step length and width results in minimal metabolic cost (Donelan et al. 2001, 2002; Cavanagh and Williams 1982), it is reasonable to assume that movement economy contributes to selection of alternate foot placement.

Different studies have found a significant correlation between metabolic cost measured through the rate of oxygen consumption and electromyography (EMG) parameters like integrated and average EMG (Henriksson and Bonde-Petersen 1974; Kyröläinen et al. 2001; Millet et al. 2002;). Henriksson and Bonde-Petersen (1974) have found a significant correlation (0.99) between IEMG (rectus femoris and vastus lateralis) and oxygen uptake rate when the load of the cycle ergometer increased. More recently, Sengupta and Das (2004) have shown that oxygen uptake and EMG activity of different arm and trunk muscles increased when performing a reaching task from normal to extreme distances. Although they did not use a correlation analysis, it is clear from their data that the increase in oxygen uptake was proportional to the increase in EMG activity. Kyröläinen et al. (2001) have found that the biceps femoris activity during braking and push-off phases of running correlated positively with the oxygen consumption when speed increased (0.48 and 0.45, respectively). Furthermore, gastrocnemius activity during the push-off phase was also correlated to oxygen consumption (0.45). Therefore, good relationship exists between EMG and metabolic cost, suggesting that an EMG index reflecting the overall change in muscle activity can be a good indication of movement economy.

**Stability determinant validation**

When standing, COM projection is within BOS; but when walking, the projection of COM describes a winding trajectory that passes by the internal margin of the foot (Winter 1991). Winter (1995) has identified a constant relationship between center of pressure (COP) and COM based on an inverted pendulum model. In the inverted pendulum model, the difference between COP and COM is proportional to horizontal acceleration of COM. The correlation between the value of COP minus COM and horizontal acceleration is high and negative. This implies that when COP is located in front of COM, the direction of horizontal acceleration of COM is backward, and vice-versa. In practical terms, COP is always "tracking" COM and passing in front of it in order to bring COM back to the centre of BOS. The same principle is applied in the ML direction.

According to Karčnik (2004) walking systems are divided into two groups: systems that use static stability, and systems that use dynamic stability. In a static walking system, the center of mass (COM) projection is always inside the base of support (BOS) defined by the points of contact in the ground. The advantage of such system is that stability is not an issue when walking. Biped walking is a clear example of a mechanism that depends on dynamic stability (Patla 2003). During human walking, COM is inside BOS in the AP direction only during double support phase (Winter 1995). During the entire stance/swing phase, COM is outside of BOS and proper foot placement is necessary to determine COP position in the next support period in order to re-establish balance (Patla 2003; Winter 1995; Redfern and Schumann 1994). Redfern and Schumann (1994) have proposed that foot placement of the swing limb is dependent on the stance limb location relative to the pelvis, so that at heel contact the stance and swing limbs have a similar angle relative to the pelvis in both frontal and sagittal planes.

Since the combined head-arms-trunk (HAT) segments correspond to 2/3 of the body mass, maintenance of HAT verticality is crucial for stable walking. Winter (1987) has shown that there is a trade-off between hip and knee moment of force in the plane of progression in order to maintain support against gravity and HAT stability. In the frontal plane, MacKinnon and Winter (1993) have shown that the control of COM acceleration in the ML direction is a function of lateral foot placement and this is decided by events during the preceding swing phase. Foot placement determines the amount of passive destabilizing moment of force due to trunk weight that needs to be actively compensated by hip muscles.

As mentioned above, stability is one of the determinants used by the control system to select alternate foot placement. The continuous change in BOS during walking and its relationship to balance restoring mechanisms makes the COM-BOS relationship a good indicator of whole body stability. Thus, this relationship will be used to validate the stability determinant when selecting alternate foot placement.

**Maintenance of forward progression validation**

Maintenance of forward progression is related to walking towards an end-point goal. Thus, deviations that could affect this end-point goal are believed to be avoided. Patla et al. (1999) have shown that people prefer changes in the plane of progression over changes in the frontal plane. Bahrami and Patla (2005) have modeled alternate foot placement selection and have included a function to penalize alternate foot placements that would create a deviation from the end-point goal higher than 1°. The best way to capture such deviations is to look at COM trajectory, particularly how it deviates from the end-point goal. Validation of maintenance of forward progression determinant will be done by looking at COM deviation from the straight line path.

## Studies proposed

The coming chapters will describe the three studies that comprise this thesis, followed by a general discussion. The first study (Chapter 2) was proposed to validate the virtual planar obstacle paradigm that is used in all studies described here and also in previous work done by Patla et al. (1999). The second purpose of this study was to validate the economy assumption behind the minimum foot displacement determinant. This study will focus on two major output parameters: foot and trunk kinematics and lower limb muscle activity. The second study (Chapter 3) addresses the validation of stability and maintenance of forward progression determinants by looking at whole body center of mass position and velocity. The third study (Chapter 4) addresses the generality of these three determinants in a more complex terrain, and also, it focus on the nature of visual information by looking at gaze behavior while performing the avoidance task. Each of these three chapters is organized as individual articles containing introduction, methods, results and discussion sections. The general discussion at the end attends the purpose of organizing all the findings in the framework of the alternate foot placement model (Figure 1).

# Chapter 2

# Determinants guiding alternate foot placement selection and the behavioral responses are similar when avoiding a real or a virtual obstacle

## Introduction

Alternate foot placement has been studied using a virtual planar obstacle projected on a screen of an LCD monitor (Moraes and Patla 2005; Moraes at al. 2004; Gonçalves et al. 2004; Greig et al. 2004) or using a mechanical apparatus and a light projection system (Patla et al. 1999). Such a "virtual" obstacle is used to replicate an area that is considered undesirable such as a hole in the ground which must be avoided. This paradigm offers several advantages. First, it allows us to investigate the effects of available time on alternate foot placement selection. Second, different shapes can easily be created to probe the selection process. Third, it makes it possible to introduce unexpected changes in obstacle location and/or size to explore planning process. Although this paradigm offers an elegant approach to studying alternate foot placement, it is important to establish that the responses are similar to those occurring in natural environment (Kingstone et al. 2003). The first objective of this study is to validate the use of this paradigm, for the purpose of studying alternate foot placement selection in the laboratory. In order to do this we compared behavioural responses when participants were asked to avoid the virtual planar obstacle and to when they were required to avoid stepping in a hole of similar dimension and orientation. A hole is a very common obstacle present in sidewalks and trails; improper foot placement can compromise stability and result in an injury such as an ankle sprain. Visual sampling around the hole has been shown to increase for proper foot placement (Patla et al. 1996). We controlled when participants saw the hole, real or virtual, by externally controlling the LCD goggles worn by the participants. Behavioral data including limb end-point kinematics and muscle activity of various muscles were collected. Changes in muscle activation profiles allowed us to directly assess if, as suggested by our previous work

(Moraes et al. 2004; Patla et al. 1999), economy determinant which minimizes energy demand, is important in selecting alternate foot placement.

Different studies have shown a positive correlation between muscle activity and oxygen uptake (Henriksson and Bonde-Petersen 1974; Kyröläinen et al. 2001; Millet et al. 2002; Sengupta and Das 2004). In general, the increase in metabolic cost is seen as a consequence of increased muscle activity associated with the movement (Gottcchall and Kram 2003). In fact, Praagman et al. (2003) showed a good linear relationship between EMG and oxygen consumption within a muscle, with correlations higher than 0.8 between average-EMG and metabolic cost. Therefore, it is expected that changes in electromyography (EMG) will be proportional to energy demands required for changes in foot displacement. An EMG index involving the net change in muscle activity during alternate foot placement will be correlated against foot displacement to further validate the economy determinant.

In addition, the present study addresses the adaptive capabilities of locomotor function when individuals internally and intentionally initiate it while walking. Previous studies have looked at stride length modulation when the task was defined *a priori* (Patla et al. 1989b; Varraine et al. 2000). In Patla et al's study participants were requested to lengthen the step after an audio cue was presented at different phases of the gait cycle (i.e., ipsi- and contralateral heel-contact and toe-off). Varraine et al. (2000) requested participants to intentionally modify stride length during two blocks of trials by lengthening and shortening the step after every fifth stride. Although these studies investigated the control mechanisms of stride modulation, they both used manipulations in which stride modulation was defined *a priori,* and they investigated only stride length modulations. The alternate foot placement paradigm offers a different type of manipulation because it asks participants to *choose* changes in stride length/width in order to avoid an undesirable area; stride modulation is not defined *a priori*. In this scenario, participants need to identify the stimulus (i.e., undesirable area), select the appropriate response, and implement it. The previous studies do not have this selection response step because it was already defined. Additionally, the control mechanisms involved in foot placement modulation in the mediolateral direction have not been systematically studied. To date, only one study has investigated this phenomenon, and it analyzed only step widening (Patla 1991). Therefore, the third purpose of the present study is to analyze how subjects without prior knowledge of the task modulate stride length/width while walking on the ground. For this analysis, changes in electromyography (EMG) profiles will be used.

## Method

### *Participants*

Eight participants volunteered for this study (6 F and 2 M; age 20.9 years SD 3.4; height 1.72 ±0.11 meters; mass 66.2 ±11.4 kilograms). None of the participants had any neurological, muscular, or joint disorders that could affect their performance in this study. Procedures used in this study were approved by the Office of Research Ethics at the University of Waterloo.

### *Protocol*

Before starting the experiment, participants were asked to walk on the pathway at a self-selected pace; maintaining the same walking pace throughout the experiment. Individuals started walking two strides from the obstacle location region such that the right foot would land on the middle of the monitor/hole when present and as illustrated in Figure 1. A trigger mat was placed at the end of the first stride. Participants performed two blocks of trials (real and virtual) and in both blocks they were instructed to avoid stepping on the undesirable area. In the real condition, the undesirable area was an actual hole in the walkway, whereas in the virtual condition it was a planar virtual obstacle. The planar virtual obstacle was projected on a LCD monitor (Samsung SyncMaster™ TFT 181T Black) embedded in the walkway. A piece of Plexiglas™ was placed over the monitor so that participants could step over it normally. Virtual and real obstacles were white and the walkway was covered with a black carpet in order to guarantee good contrast. In both conditions, two obstacle sizes in three different locations were used (Figure 1). The obstacle sizes were: 1) 38 x 10 cm and 2) 12.5 x 30 cm. Participants wore a pair of LCD goggles (Lucent Technologies). The status of the goggles was changed from opaque to transparent almost immediately at right heel-contact (HC) on the trigger mat. While opaque, the goggles completely prevented the participants from gaining information about the visual surroundings and movements of the body through vision.

At the beginning of each trial, participants stood at the start position (individually adjusted) with the LCD goggles closed. The verbal command “Ready” informed the participants that the trial was to begin soon. With the subsequent verbal command “Go”, they initiated walking (with left limb first) and at the right HC on the trigger mat the LCD goggles were opened, so that participants could see the surroundings and plan/implement an alternate foot placement if an obstacle was present. Participants had two steps in which to plan and implement the alternate foot placement. Participants were instructed to keep walking normally until they reached the end of the walkway and to stand there for one second before turning around and returning to the start point. The dimensions of the virtual and real obstacles were the same and the depth for the real hole was set at 6 cm. Participants performed thirty avoidance trials (five trials per obstacle position) and thirty walk-through (WT) trials for each condition. Therefore, probability of obstacle appearance was equal to 50%. Trials within each block were completely randomized. The starting block was counterbalanced across participants; for four participants the first block of trials was with the real hole, whereas for the other four participants the first block of trials was the virtual obstacle. Participants were videotaped during the data collection. At the end of the experimental session, participants' feet were traced on a sheet of paper for the predicted minimum foot displacement calculations (see below).

Ten infrared emitting-diodes (IREDs) markers were placed bilaterally over five anatomical landmarks: 5$^{th}$ metatarsal, heel, lateral malleolus, greater trochanter, and greater tubercle of humerus. Three OPTOTRAK™ cameras (Northern Digital, Waterloo, Canada) were positioned in front of the participants to track the IREDs markers at 60 Hz. Fourteen channels of EMG were recorded using adhesive, bipolar, Ag/AgCl surface, disposable electrodes, placed bilaterally with a center-to-center spacing of 3 cm over the belly of the following muscles: tibialis anterior (TA), medial gastrocnemius (GA), rectus femoris (RF), biceps femoris (BF), gluteus medius (GM), adductor longus (AL), and erector spinae at L3-L4 location (ES). Electrodes' positioning were based on descriptions provided by Delagi and Perotto (1980) and Winter (1991). The signals were A/D converted at a sampling rate of 2400 Hz. The EMG data were collected using a differential amplifier (Octopus AMT, Bortec Electronics Inc., Calgary, Canada) with the gain varying from 500 to 1000 across muscles. This amplifier has an input impedance of ~10 GOhm, and CMRR of 115 dB (at 60 Hz).

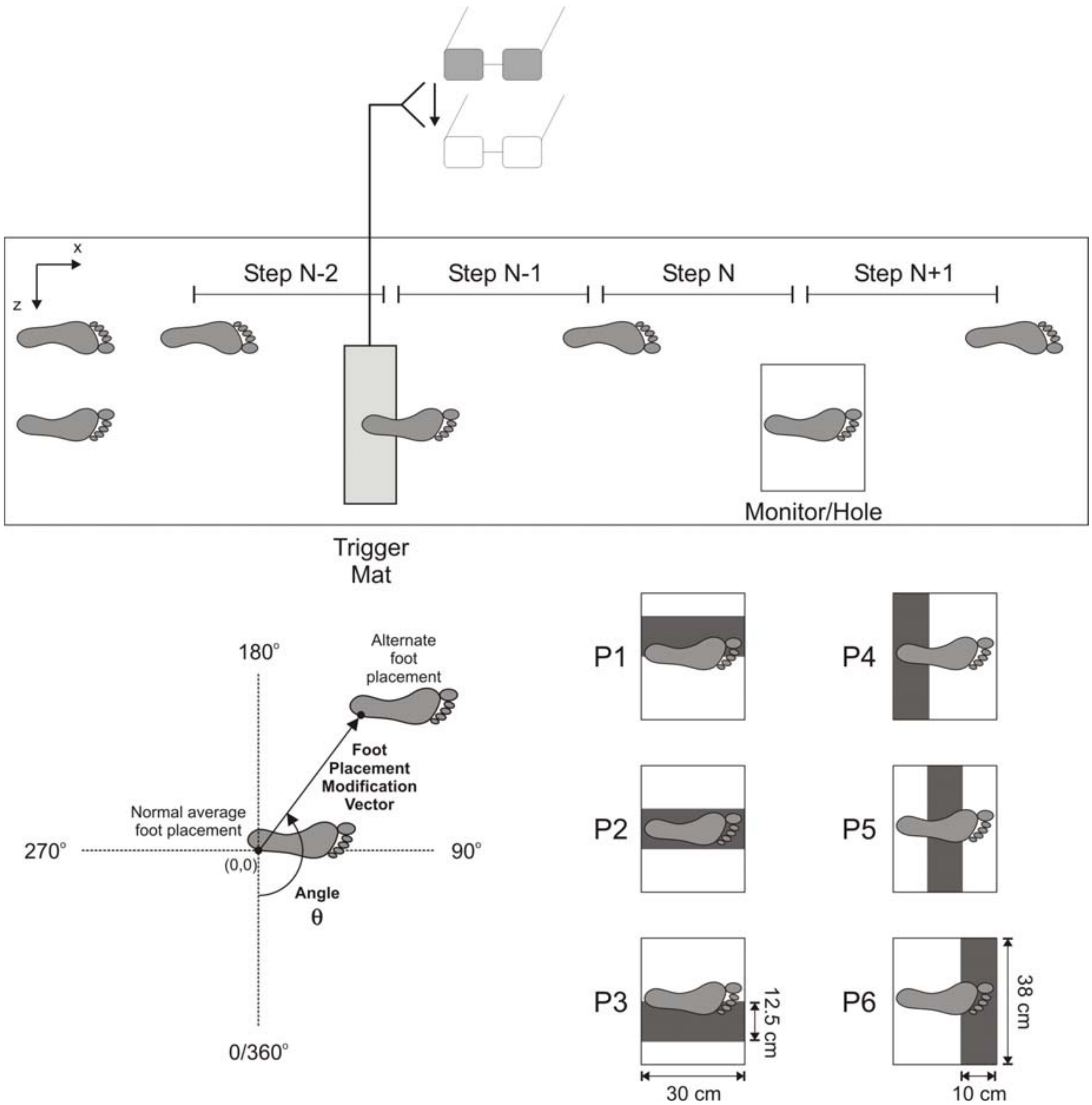


*Figure 1*. A bird's eye-of-view of the experimental setup is shown on the top. Participants were instructed to begin walking with their left foot first. The trigger mat was placed at the region of the first right heel contact (RHC). The obstacle was located one stride after the RHC. The bottom left shows the foot placement modification vector, which is calculated based on the average foot placement. The bottom right shows the location of the six obstacles used in this study relative to the normal landing position of the foot. For P1, P2, and P3 obstacle dimensions are the same, only the location is different. The same is the case for obstacles P4, P5, and P6.

## *Data analysis*

Marker coordinates were filtered using a fourth-order zero lag low-pass digital

Butterworth filter with a cut-off frequency of 6 Hz. Ankle markers were defined as the limb end-point and used to calculate the foot placement modification vector (Figure 1). For each obstacle/hole trial, the x and z coordinates of the ankle marker were subtracted from the average coordinates of the WT trials at heel-contact; these are called relative coordinates (RCs). HC was identified through visual inspection of the feet stick figures using Optofix software (Mishac Kinetics). The average values of the coordinates for the WT trials were obtained from 10 randomly selected trials within each condition. The RCs were used to calculate the foot placement modification vector magnitude and orientation (i.e., angle). Vector orientation was used to define the alternate foot placement choice: lateral adjustment (0° - <45° and >315° - 360°), long adjustment (45° - <135°), medial adjustment (135° - <225°), and short adjustment (225° - <315°). Percentage of adjustments in each direction for each obstacle position was calculated relative to the total number of trials participants successfully performed for each condition independently.

In order to quantify whether foot placement modification vector orientation was affected by condition, the mean foot placement modification vector orientation (i.e., angle) was calculated for each participant for the dominant choice in each obstacle position using circular statistics (Batschelet 1981). Next, the absolute difference between the angles for the real and virtual conditions was computed and the cosine of this difference was used for the statistical analyses. A cosine equal to 1.0 indicates that there is no difference between the foot placement modification vector orientation for the real and virtual conditions.

Predicted minimum foot displacement (PMFD) was calculated for the four options (long, short, lateral, and medial) for each obstacle position and condition. PMFDs for two obstacle positions are illustrated in Figure 2 and were computed as follows:

$$\mathrm{PMFD}_{\mathrm{Long}} = \left(\mathrm{LL}_{x} - \mathrm{Avg}_{x}\right) + \mathrm{HAD} \qquad \text{Equation 1}$$

$$\mathrm{PMFD}_{\mathrm{Short}} = \left(\mathrm{AMD} + \mathrm{MED}\right) - \left(\mathrm{SL}_{x} - \mathrm{Avg}_{x}\right) \qquad \text{Equation 2}$$

$$\mathrm{PMFD}_{\mathrm{Lateral}} = \left(\mathrm{LaL}_{z} - \mathrm{Avg}_{z}\right) + \mathrm{FW} \qquad \text{Equation 3}$$

$$\mathrm{PMFD}_{\mathrm{Medial}} = \mathrm{Avg}_{z} - \mathrm{MeL}_{z} \qquad \text{Equation 4}$$

where LL, SL, LaL, and MeL define the distance from the center of the obstacle to the top, bottom, right, and left edges respectively, HAD is the heel-ankle distance, AMD is the ankle-metatarsal distance, MED is the metatarsal-edge distance, FW is the foot width, and Avg is the average foot placement in the WT trials.

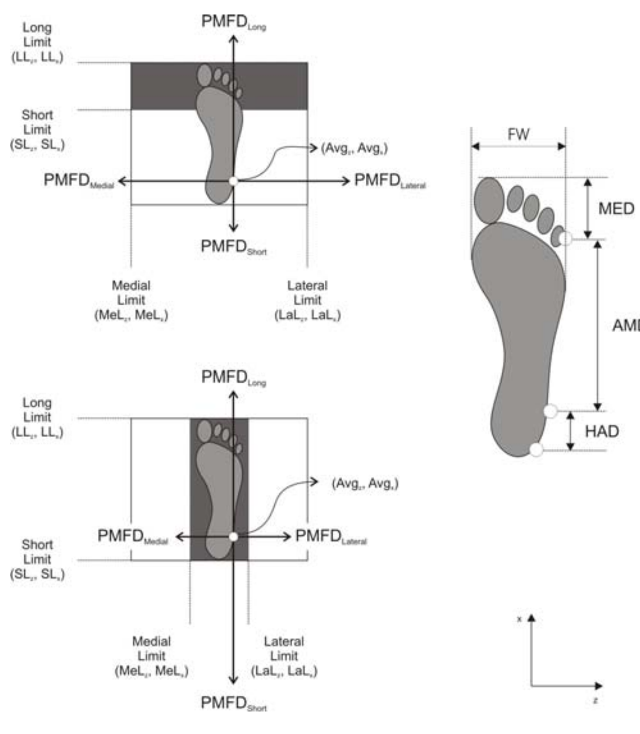


*Figure 2*. Predicted minimum foot displacement (PMFD) is shown for two different obstacles (P6 on the top and P2 on the bottom). The length of the arrow indicates the magnitude of the PMFD in four directions (long, short, lateral, and medial). The obstacles limits are also shown for the four possible choices. These limits were used in the calculation of the PMFD (see text for details). The foot on the right side shows the markers' locations and the respective distances between them (HAD: heel-ankle distance; AMD: ankle-metatarsal distance; MED: metatarsal-edge distance; FW: foot width). MED was calculated as the difference between mean foot length and AMD plus HAD.

In order to identify the contribution of each step to the final change in foot placement, a variable called relative adjustment (RA) was computed (Moraes et al. 2004), according to Equations 5 and 6:

$$RA_{N-1} = \frac{RC_{N-1}}{RC_N} \qquad \text{Equation 5}$$

$$RA_N = \frac{(RC_N - RC_{N-1})}{RC_N} \qquad \text{Equation 6}$$

where RA is the relative adjustment, RC is the relative coordinate, N-1 is the step before the adaptive step, and N is the adaptive step. For the long/short adjustments, the $RC_x$ (i.e., anteroposterior coordinate) was used for RA calculation and $RC_z$ (i.e., mediolateral coordinate) was used for the RA calculation for the lateral/medial adjustments.

Trunk markers (greater trochanter and greater tubercle of humerus) were used to calculate trunk center of mass ($T_{COM}$) position according to Winter (2005). $T_{COM}$ velocity was calculated as the first derivative of $T_{COM}$ position using the central difference procedure. Dynamic stability was quantified as proposed by Hof et al. (2005). In this analysis, the $T_{COM}$ position is extrapolated based on the $T_{COM}$ velocity direction and magnitude. This extrapolated $T_{COM}$ (XcoM) is given by the following equation:

$$XcoM = T_{COM} + \frac{\dot{T}_{COM}}{\omega_0} \qquad \text{Equation 7}$$

where $T_{COM}$ is the actual center of mass position, $\dot{T}_{COM}$ is the velocity of the center of mass, and $\omega_0$ is equal to $\sqrt{g/\ell}$ (g is the acceleration due to gravity and $\ell$ is the height of $T_{COM}$). Since the $T_{COM}$ height is not adequate for this calculation, an approximation of $\ell$ is used. According to Hof et al. (2005), in the frontal plane $\ell$ is equivalent to 1.34 times the height of the greater trochanter; whereas in the sagittal plane it is 1.24 times the height of the trochanter. The distance between XcoM and the maximum reach of the center of pressure (COP) is then used as a stability index called margin of dynamic stability (MDS). Since we do not have COP measures, the maximum reach of COP was estimated based on 5$^{th}$ metatarsal and heel markers for the AP and ML directions, respectively. The dynamic stability margin (MDS) was calculated at HC.

Maintenance of forward progression was assessed by calculating the $T_{COM}$ deviation from the AP axis in the transverse plane. $T_{COM}$ in steps N-1 and N were used to compute forward progression deviation at alternate foot placement, whereas $T_{COM}$ in steps N and N+1 were used to compute forward progression deviation after alternate foot placement. Negative angle values indicate a deviation to the left, and vice-versa for positive angles.

EMG signal was full wave rectified and digitally filtered using a fourth-order zero lag low-pass Butterworth filter with a cut-off frequency of 10 Hz (Patla et al. 1991). For each participant, ten WT trials (the same trials used for the kinematics analysis) were used to determine the normal EMG profile for each condition separately (real and virtual). The normal EMG profiles were used for identifying changes in muscle activation when avoiding the obstacle. For each condition and obstacle position, EMG data were grouped according to the choice made and ensemble averaged from right heel-contact on the trigger mat to right heel-contact of the alternate foot placement and normalized to the peak value of the normal walking (WT trials) as suggested by Yang and Winter (1984). WT trials were also ensemble averaged and normalized. For each condition, the normalization values were defined based on the correspondent WT condition (i.e., real or virtual).

Changes in muscle activation were analyzed in four phases of the gait cycle as suggested by Patla et al. (1991): 1% - 30% (weight acceptance), 31% - 50% (push-off), 51% - 80% (pull-off), and 81% - 100% (late swing). Within each sector, the average profile of each muscle of the experimental trial was compared against the normal EMG profile plus/minus one standard deviation for the respective muscle. In order to identify a change in muscle activation, a four-threshold procedure was used. The first threshold consisted of a deviation above or below the normal variability. A deviation was considered as a change in muscle activity only if it lasted for at least three data points (second threshold). In the case where changes where present above and below the normal variability within the same phase of analysis, the net change in muscle activity was computed (third threshold). The net change consisted of summing the area above the normal variability and the area below the normal variability within the phase of analysis. Positive and negative values for the above and below thresholds, respectively, were used to define the EMG difference profile as illustrated in Figure 3. Taking the pull-off phase of Figure 3 as an example, the excitation area (i.e., positive side) and the inhibition area (i.e., negative side) were summed. In this case, the net change was positive, which indicated an increase in muscle activation within the pull-off phase. In addition, when more than one positive/negative area was present they were added together before computing the net change. Only consistent changes in muscle activation across participants were considered as relevant. Therefore, the same net change needed to be present in at least N-1 participants who exhibited the same choice defining the fourth threshold.

For the validation of the economy assumption, the relationship between the net change in muscle activity within one stride and the amount of foot displacement was analyzed. A variable relating the change in muscle activation within the adaptive stride to the muscle activation during normal walking was used as an EMG index. Percentage change in muscle activation (PCMA) for each muscle was calculated according to Equation 8:

$$\mathrm{PCMA} = \left( \frac{\Delta \mathrm{EMG}_{\mathrm{Area}}}{\mathrm{EMG}_{\mathrm{AreaNormal}}} \right) \times 100 \qquad \text{Equation 8}$$

where $\Delta EMG_{Area}$ is the net change in integrated muscle activation within one stride and $EMG_{AreaNormal}$ is the area under the ensemble averaged profile for the WT trials. Changes in muscle activation of each muscle were summed in order to get the percentage change in total muscle activation (PCTMA) according to Equation 9:

$$\mathrm{PCTMA} = \sum_{i=1}^{14} \mathrm{PCMA}_i \qquad \text{Equation 9}$$

where *i* is the number of muscles analyzed.

*Statistical analyses*

For each obstacle position, a two-way (Condition x Choice) chi-square analysis ($\chi^2$) was carried out in order to identify whether the preferred choice in the real and virtual conditions are different. For the PMFD, two-way ANOVAs (Condition x Option) with repeated measures in both factors were carried out for each obstacle position separately. Since the dominant choice was the same for the P1 and P2 obstacles, they were always included in the same analysis. For the cosine of the difference between foot placement modification vector orientations for the real and virtual conditions, a one-way ANOVA (Step) with repeated measures was carried out for each obstacle position separately, except for the P1 and P2 obstacles that were included in the same analysis (two-way ANOVA (Obstacle Position x Step) with repeated measures). For all other dependent variables, two-way ANOVAs (Condition x Step) with repeated measures in both factors were performed for each dominant choice per obstacle. The dominant choice for the P5 obstacle was not included in any analysis because of the inconsistency among subjects. Some subjects in only one trial chose the dominant adjustment, which is not quite representative. For the medial analysis (i.e., P3 obstacle), only six participants were included, since two of the participants never chose the medial adjustment for the P3 obstacle in the real condition. Significant alpha value was set at 0.05. When main or interaction effects were found, Least Squares Means post-hoc analysis was used to identify which treatments differ from one another.

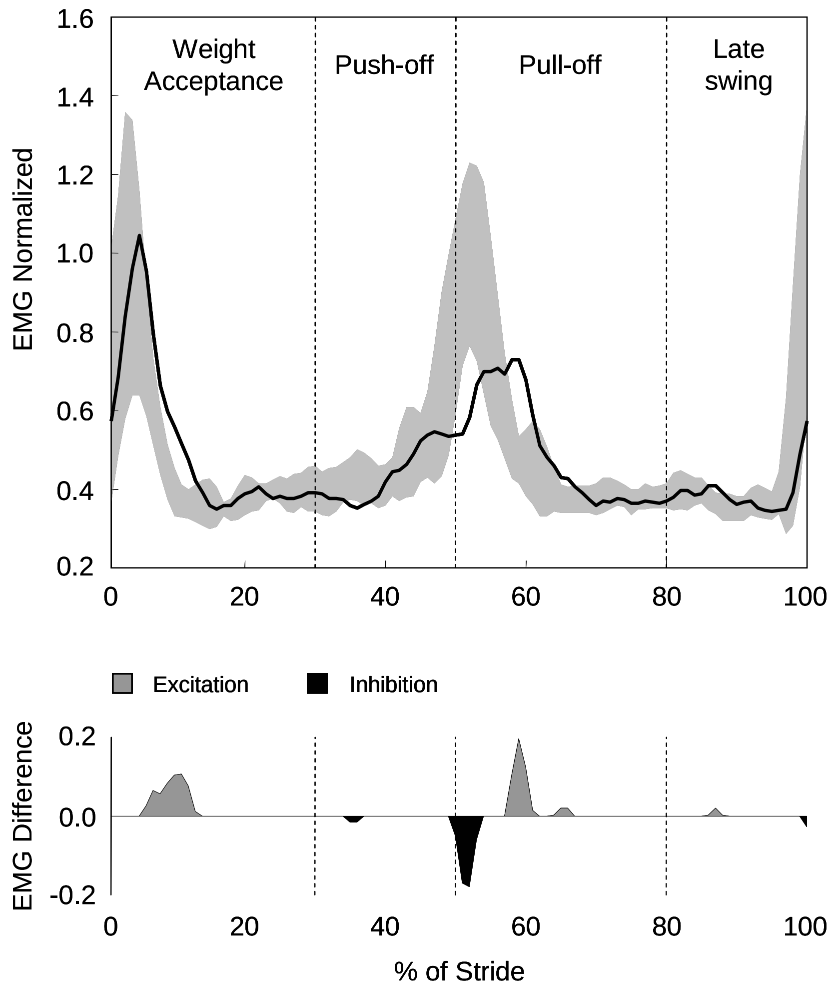


*Figure 3.* Top part shows the mean ± 1 standard deviation EMG profiles for the WT data (shaded area) as well as the ensemble average profile for the experimental condition for the erector spinae (continuous line) from right heel contact on the trigger mat to right heel contact of the alternate foot placement (i.e., one stride). Bottom part shows the electromyography (EMG) area that is either above or below the variability for the WT trials. Excitation values are positive and inhibition values are negative.

Regression analyses between PCTMA and mean foot placement modification vector magnitude were carried out independently for the real and virtual obstacle conditions. The regression analyses included within and across participants data. Data from all the choices made for each obstacle position were used in these analyses. A given pair of data was included in the regression analysis only if the participant chose the option in at least two trials.

## Results

*Are the alternate foot placement choices affected by the conditions?*

The percentage of alternate foot placement choices in each direction is shown in Figure 4. Two-way (Condition: real and virtual x Choice: long, short, medial, and lateral) $\chi^2$ analyses for each obstacle separately showed that there was no significant difference in the alternate foot placement choices between real and virtual conditions. As expected, lateral, medial, short, and long adjustments were the dominant choices for the P1, P3, P4, and P6 obstacles, respectively. For the P2 obstacle, the dominant choice was the lateral adjustment. For the P5 obstacle, there was a slight trend of choosing to step long than short.

*Is the predicted minimum foot displacement different between conditions?*

For the PMFD, the two-way repeated measure ANOVAs (Condition: real and virtual x Option: long, short, medial, and lateral) for each obstacle position identified a main effect only for option (P1: $F_{3,21} = 423.00$, $p < 0.0001$; P2: $F_{3,21} = 338.48$, $p < 0.0001$; P3: $F_{3,21} = 410.54$, $p < 0.0001$; P4: $F_{3,21} = 305.89$, $p < 0.0001$; P5: $F_{3,21} = 35.57$, $p < 0.0001$; P6: $F_{3,21} = 200.21$, $p < 0.0001$). Post-hoc analysis showed that for the P1 to P3 obstacles, long and short PMFDs (long = 30.3 cm; short = 27.9 cm) were always larger than medial and lateral PMFDs. In addition, long PMFD was larger than short PMFD in these three obstacles. For the P1 obstacle, the smallest PMFD was observed for the lateral option (5.3 cm) followed by the medial option (17.8 cm). For the P2 obstacle, there was no difference for the PMFD between lateral (11.3 cm) and medial (11.8 cm) options. For the P3 obstacle, the smallest PMFD was found for the medial option (5.8 cm), followed by the lateral option (17.3 cm).

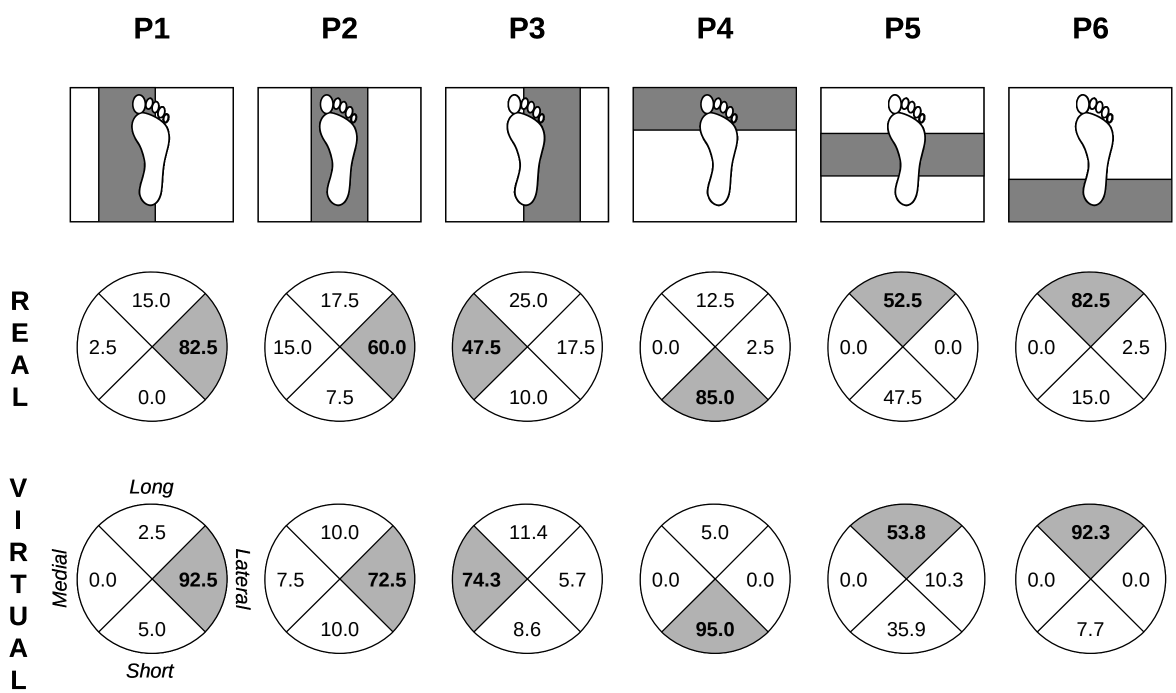


*Figure 4*. Top row shows the obstacle location. Percentage values for the four possible choices for each obstacle position for the real and virtual conditions are shown in the middle and bottom rows, respectively. For each pie graph, the top value is the percentage for long choices, the bottom value is the percentage for short choices, the left value is the percentage for medial choices, and the right value is the percentage for lateral choices. The shaded area indicates the dominant choice for each obstacle.

For the P4 to P6 obstacles, lateral and medial PMFDs were equal to 24.3 cm and 24.8 cm, respectively, and they were not different from each other. For the P4 obstacle, short option (7.9 cm) exhibited the smallest PMFD, and the longest PMFD was found for the long option (30.3 cm). For the P5 obstacle, the smallest PMFD was observed for the short option (17.9 cm), followed by the long option (20.3 cm). For the P6 obstacle, the smallest PMFD was observed for the long option (10.3 cm), whereas the longest PMFD was found for the short option (27.9 cm).

*Are foot placement modification vector magnitude and orientation affected by the conditions?*

Foot placement modification vector distribution for each obstacle position and condition for four steps are shown in Figures 5 and 6. For the dominant choices, the distributions are similar for the two experimental conditions. In order to identify whether the foot placement modification vectors were similar between conditions, the magnitude of these vectors and the angle difference between them were statistically analyzed. Mean and standard deviation of the dominant choice for each obstacle position are shown in Figure 7. For the foot placement modification vector magnitude, the two-way repeated measure ANOVA (Condition: P1R, P2R, P1V, P2V x Step: N-1, N, and N+1) for the lateral choice (P1 and P2 obstacles) identified main effects of condition ($F_{3,21} = 5.76$, $p = 0.0049$) and step ($F_{2,56} = 70.06$, $p < 0.0001$) as well as an interaction effect ($F_{6,56} = 6.73$, $p < 0.0001$). The interaction effect showed that in step N-1, foot placement modification vector magnitude was larger for the real condition than for the virtual condition for the P1 obstacle. No difference between conditions was observed for the other two steps. In addition, foot placement modification vector magnitude was larger for the P2 obstacle than for the P1 obstacle for steps N and N+1. No difference was observed in step N-1. For the P3 (medial choice) and P6 (long choice) obstacles, the two-way repeated measure ANOVAs

(Condition: P3R / P3V or P6R / P6V x Step: N-1, N, and N+1) identified main effects only for step (P3: $F_{2,20} = 7.82$, $p = 0.0031$; P6: $F_{2,28} = 29.40$, $p < 0.0001$). In both analyses, foot placement modification vector magnitude for steps N and N+1 were larger than foot placement modification vector magnitude for step N-1. For the P4 obstacle (short choice), the two-way repeated measure ANOVA (Condition: P4R and P4V x Step: N-1, N, and N+1) revealed a main effect of step ($F_{2,28} = 58.16$, $p < 0.0001$) as well as an interaction effect ($F_{2,28} = 10.60$, $p = 0.0004$). The interaction effect revealed that there was no difference between real and virtual conditions in step N, but for the other two steps there were significant differences. In step N-1, foot placement modification vector magnitude was larger for the real condition than for the virtual condition and vice-versa in step N+1.

The cosine of the foot placement modification vector orientation difference between real and virtual conditions was used to identify whether the foot placement modification vector orientation was similar between these two conditions. For the P1 and P2 obstacles (lateral choice), the two-way repeated measure ANOVA (Obstacle Position: P1 and P2 x Step: N-1, N, and N+1) indicated a main effect of obstacle position ($F_{1,7} = 12.78$, $p = 0.0090$) and step ($F_{2,28} = 17.16$, $p < 0.0001$). The cosine is higher for the P2 obstacle than for the P1 obstacle, probably due to the negative value in step N-1 for the P1 obstacle (Figure 7). The step effect showed that in step N the foot placement modification vector orientation in real and virtual conditions were very similar, which slightly decreased in step N+1. In step N-1, there was clearly no similarity between real and virtual conditions for the foot placement modification vector orientation. Although Figure 7 shows an almost zero cosine value in step N-1 for the P3 obstacle (medial choice), the one-way repeated measure ANOVA (Step: N-1, N, and N+1) just failed to achieve significance ($p = 0.0779$) probably due to the very high variability in this step (0.76). For the P4 and P6 obstacles (short and long choices, respectively), the one-way repeated measure ANOVA (Step: N-1, N, and N+1) revealed a main effect of step (P4: $F_{2,14} = 6.17$, $p = 0.0120$; P6: $F_{2,14} = 6.27$, $p = 0.0114$). In both choices, there was no difference between steps N and N+1, which also exhibited a very high positive cosine value indicating that the foot placement modification vector orientation was similar between the real and virtual conditions. Step N-1 showed a smaller cosine than steps N and N+1 in both choices.

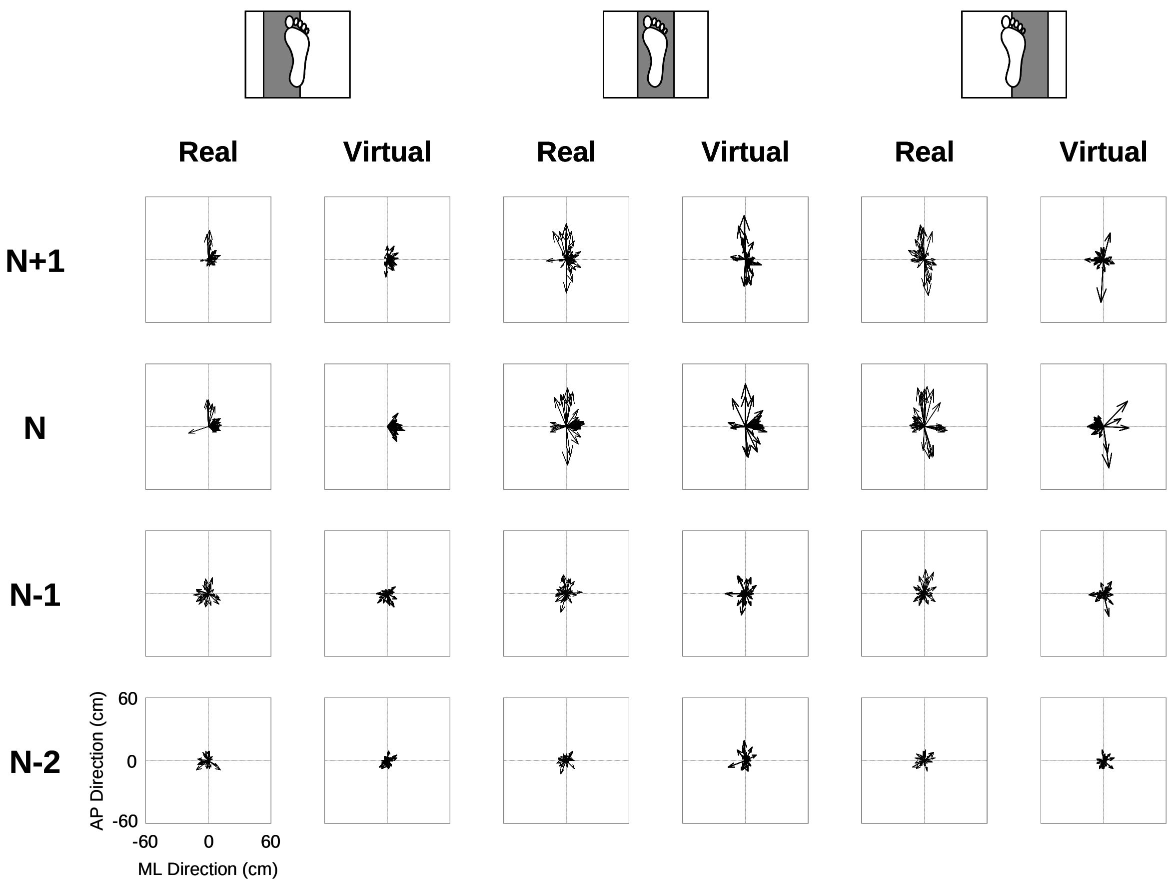


*Figure 5.* Vector distribution for four steps (N-2, N-1, N, and N+1) for obstacle positions P1 (first two columns), P2 (third and fourth columns), and P3 (last two columns) for the real and virtual conditions.

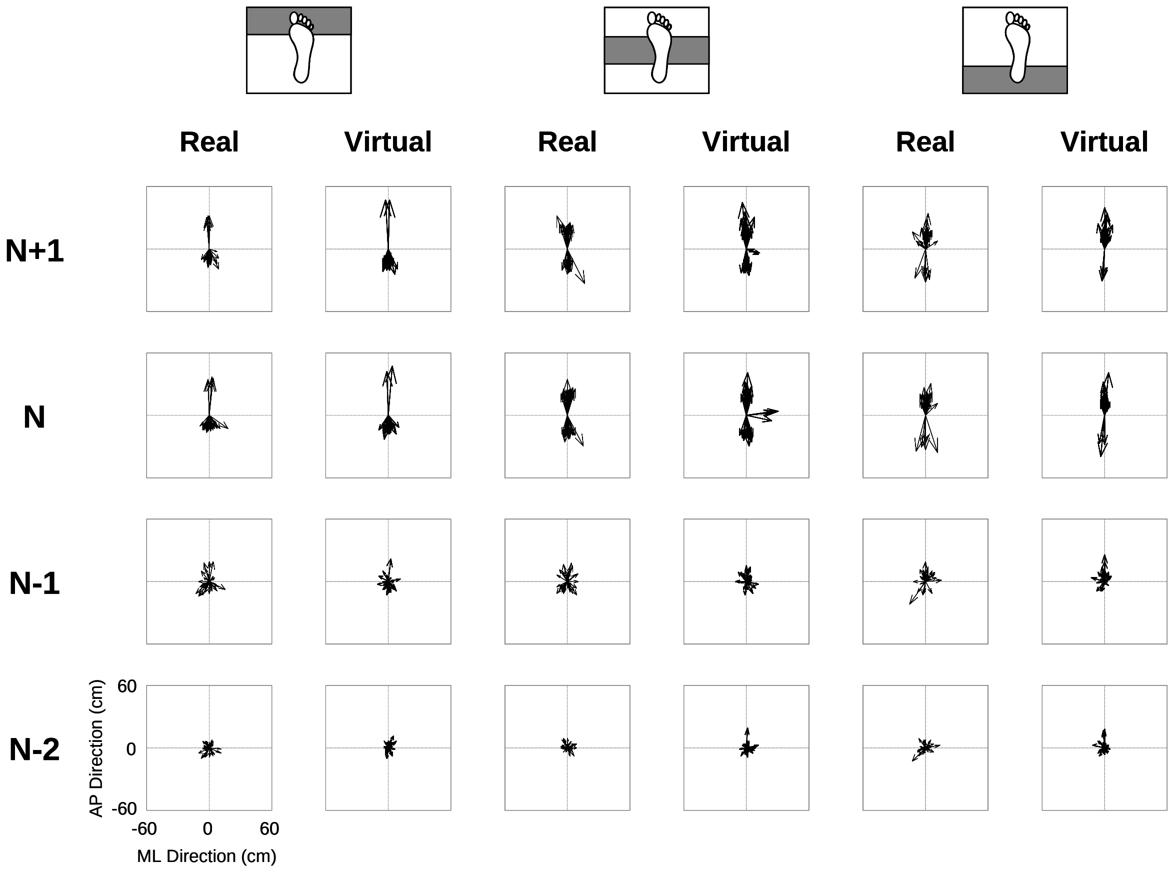


*Figure 6*. Vector distribution for four steps (N-2, N-1, N, and N+1) for obstacle positions P4 (first two columns), P5 (third and fourth columns), and P6 (last two columns) for the real and virtual conditions.

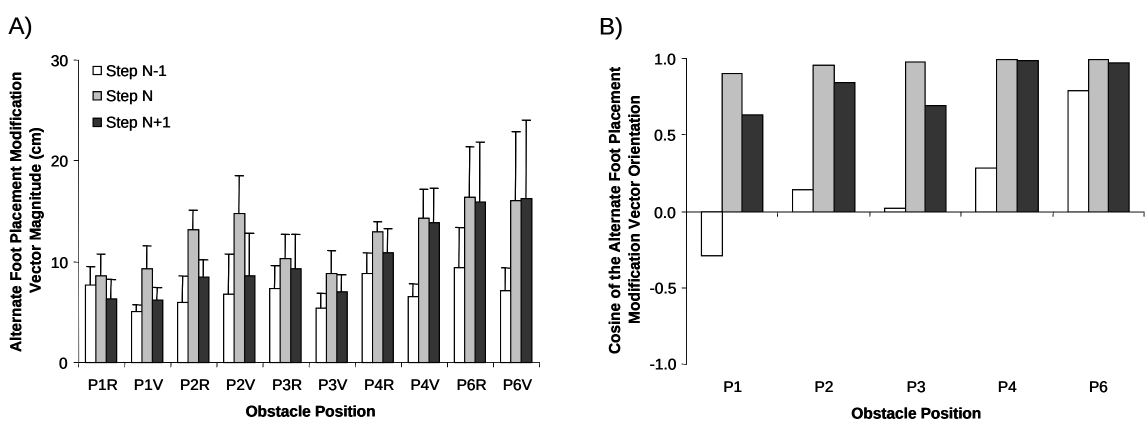


*Figure 7*. A) Mean and standard deviation of the foot placement modification vector magnitude in both real (R) and virtual (V) conditions. B) Mean of the cosine of the foot placement modification vector orientation difference between real ($\theta_R$) and virtual ($\theta_V$) conditions for three steps (N-1, N, and N+1). Data for five obstacle positions are shown (P1, P2, P3, P4, and P6).

*How is the dynamic stability regulated for the avoiding the real versus virtual hole?*

There was no difference in MDS between the real and virtual condition for all choices analyzed. Mean and standard deviation for the MDS in both AP and ML directions are shown in Figure 8. For the P1 and P2 obstacles (lateral choice), no main or interaction effects were found in the AP direction. In the ML direction, a two-way repeated measure ANOVA (Condition: P1R, P1V, P2R, P2V, WTR, WTV x Step: N-1, N, N+1) identified main effects of condition ($F_{5,35} = 12.88$, $p < 0.0001$) and step ($F_{2,84} = 76.90$, $p < 0.0001$) as well as an interaction effect ($F_{10,84} = 5.22$, $p < 0.0001$). The post-hoc analysis for the interaction effect revealed that MDS for step N-1 was greater for the P1 and P2 obstacles compared to WT; whereas in step N, MDS increased gradually (WT < P1 < P2). No difference was observed in step N+1 among all obstacle positions, except for the comparison between P2R and WTR. No difference was found between the real and virtual condition. For the P3 obstacle (medial choice), a two-way ANOVA (Condition: P3R, P3V, WTR, WTV x Step: N-1, N, N+1) revealed only a main effect of step in the AP direction ($F_{2,40} = 3.30$, $p = 0.0471$). In the ML direction, a main effect of condition was found ($F_{3,15} = 4.86$, $p = 0.0148$). MDS was greater for the WT compared to P3 in both real and virtual conditions. No difference was found between the real and virtual condition. For the P4 obstacle, a two-way repeated measure ANOVA (Condition: P4R, P4V, WTR, WTV x Step: N-1, N, N+1) showed no main or interaction effects for the MDS in the AP direction. In the ML direction, main effects of condition ($F_{3,21} = 4.66$, $p = 0.0120$) and step ($F_{2,56} = 15.27$, $p < 0.0001$) were found. MDS for P4 was greater than WT in both real and virtual conditions. No difference was found between the virtual and real condition. For the P6 obstacle, a two-way repeated measure ANOVA (Condition: P6R, P6V, WTR, WTV x Step: N-1, N, N+1) revealed main effect of step in both AP ($F_{2,56} = 3.33$, $p = 0.0430$) and ML ($F_{2,56} = 3.39$, $p <$

0.0408) directions.

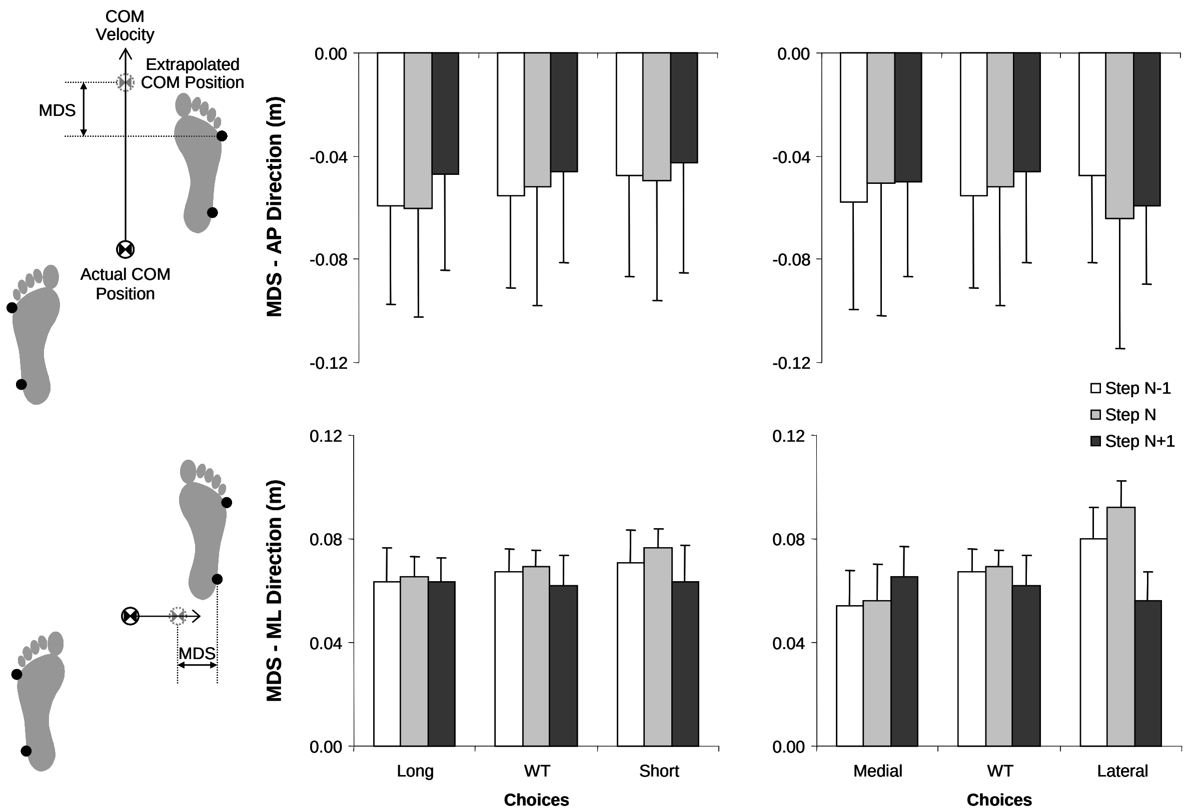


*Figure 8*. Mean and standard deviation of the margin of dynamic stability (MDS) in the anteroposterior (AP) and mediolateral (ML) directions for three steps (N-1, N, and N+1). Data is averaged across conditions for each dominant choice per obstacle. (WT: walk through; MDS: margin of dynamic stability)

*Is forward progression affected by conditions?*

No difference between conditions was found for the forward progression analyses. For the P1 and P2 obstacles (lateral choices), a two-way repeated measure ANOVA (Condition: P1R, P1V, P2R, P2V, WTR, WTV x Step: at alternate foot placement (AFP) and after AFP) revealed main (condition: $F_{5,35} = 15.31$, $p < 0.0001$; step: $F_{1,42} = 46.03$, $p < 0.0001$) and interaction ($F_{5,42} = 4.33$, $p = 0.0029$) effects. Post-hoc analysis for the interaction effect revealed that at alternate foot placement there was a deviation towards the left for the P1 and P2 obstacles, whereas for WT the deviation was towards the right. In addition, deviation for the left was higher for the P2V than for P1V at alternate foot placement. After alternate foot placement, no difference was observed between P1 and P2 in either real or virtual condition, but both obstacle positions presented a greater deviation towards the left than WT. No difference was observed between the real and virtual condition. For the P3 obstacle (medial choice), a two-way repeated measure ANOVA (Condition: P3R, P3V, WTR, WTV x Step: at AFP and after AFP) identified main effects of condition ($F_{3,15} = 6.52$, $p = 0.0049$) and step ($F_{1,20} = 63.34$, $p < 0.0001$). Post-hoc analysis for the condition effect showed a greater deviation towards the right than WT for the P3 obstacle. For the P4 obstacle (short choices), a two-way repeated measure ANOVA (Condition: P4R, P4V, WTR, WTV x Step: at AFP and after AFP) revealed only a main effect of step ($F_{1,28} = 106.91$, $p < 0.0001$). The same was observed for the P6 obstacle analysis ($F_{1,28} = 114.72$, $p < 0.0001$).

*Is the relative contribution of each step to the alternate foot placement adjustment affected by the conditions?*

For the lateral choice (P1 and P2 obstacles), a two-way repeated measure ANOVA (Condition: P1R, P1V, P2R, and P2V x Step: N-1 and N) revealed a main effect of step ($F_{1,28} = 59.90$, $p < 0.0001$). As seen in Table 1, the major adjustment was made in step N. For the medial and short choices (P3 and P4 obstacles), the two-way repeated measure ANOVAs (Condition: P3R / P3V or P4R / P4V x Step: N-1 and N) identified main effects of step (Medial: $F_{1,10} = 7.00$, $p = 0.0245$; Short: $F_{1,14} = 9.96$, $p = 0.0070$). As observed for the lateral choice, the major changes occurred in step N. For the long choice (P6 obstacle), there was no main or interaction effects. For the real condition, the RA was very similar for steps N-1 and N, but it was larger for step N than for step N-1 in the virtual condition.

However, the interaction effect was not statistically significant; probably because of the high variability in the real condition. Taken all together, these results indicate that adjustments occurred mainly in the adaptive step (i.e., step N).

*Table 1*. Relative adjustment mean (± standard deviation) for steps N-1 and N for each of the alternate foot placement choices. Results for five obstacle positions (P1, P2, P3, P4, and P6) are shown in both real (R) and virtual (V) conditions.

| Alternate Foot Placement Choice | Obstacle Position | Relative Adjustment | |
|---|---|---|---|
| | | Step N-1 | Step N |
| Lateral | P1R | -0.32 ±0.61 | 1.32 ±0.61 |
| | P1V | -0.01 ±0.34 | 1.01 ±0.34 |
| | P2R | 0.12 ±0.28 | 0.88 ±0.28 |
| | P2V | 0.07 ±0.20 | 0.93 ±0.20 |
| Medial | P3R | 0.26 ±0.35 | 0.74 ±0.35 |
| | P3V | -0.02 ±0.61 | 1.02 ±0.61 |
| Short | P4R | 0.26 ±0.44 | 0.74 ±0.44 |
| | P4V | 0.23 ±0.15 | 0.77 ±0.15 |
| Long | P6R | 0.49 ±0.30 | 0.51 ±0.30 |
| | P6V | 0.30 ±0.16 | 0.70 ±0.16 |

*Are the changes in muscle activity related to the magnitude of the foot placement modification vector magnitude?*

Figure 9 shows the plots of PCTMA versus the mean foot placement modification vector magnitude, with the trend line for each condition. For the virtual condition, the slope was equal to 4.09 and it was significantly different from zero ($t_1 = 6.10$, $p < 0.0001$). The intercept value (-9.94) was not significantly different from zero ($t_1 = -0.84$, $p = 0.41$), probably because of the high variability (SE = 11.9). The $R^2$ value indicated that changes in PCTMA explains 41% of the variability in the foot placement modification vector magnitude. The standard error of the estimate was equal to 37.0%, which means that when predicting the PCTMA, there will be an error of about 37.0% change in total muscle activation. For the real condition, the slope was equal to 4.59 and it was also significantly different from zero ($t_1 = 5.52$, $p < 0.0001$). The interception value (-13.45) was also not significantly different from zero ($t_1 = -0.88$, $p = 0.3844$), probably due to high variability (SE = 15.3). The $R^2$ value explains 35% of the variability and the standard error of the estimate was equal to 47.1%. Therefore, significant changes in the mean foot placement modification vector magnitude are explained by PCTMA in both conditions.

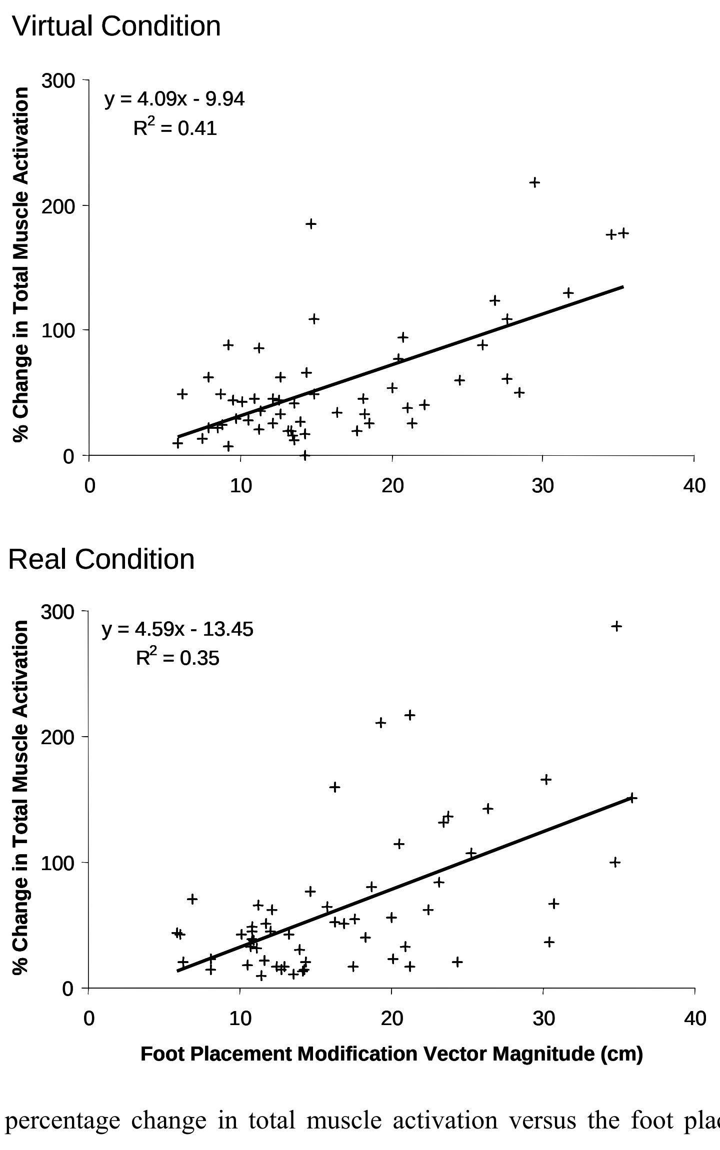


*Figure 9.* Plot of the percentage change in total muscle activation versus the foot placement modification vector magnitude for the virtual (top) and real (bottom) conditions showing the regression line and the equation relating these two variables as well as the $R^2$ value.

*How is alternate foot placement implemented?*

The changes in muscle activation for the real and virtual conditions were compared against the WT data in the real and virtual conditions, respectively. A Pearson correlation analysis for the ensemble average profile was performed for each muscle between real and virtual WT data in order to check if the baseline data was similar between conditions. As expected, the correlation coefficients were very high for all the muscles (RTA = 0.89; RGA = 0.96; RRF = 0.85; RBF = 0.85; RAL = 0.85; RGM = 0.94; RES = 0.91; LTA = 0.94; LGA = 0.95; LRF = 0.86; LBF = 0.78; LAL = 0.76; LGM = 0.94; LES = 0.92). In addition, the coefficient of variation (Winter 1991) was computed for the WT for both conditions and statistically compared using a two-way ANOVA (Condition x Muscle). The results of this analysis indicated only a main effect for muscle ($F_{13,182} = 3.96$, $p < 0.0001$). Thus, the variability is the same in both conditions. Therefore, the control data used to identify changes in muscle activation were similar and were not of concern for the differences between conditions.

Changes in muscle activity for each of the four phases are shown in Table 2. Figures 10 and 11 illustrate some of the changes in muscle activity for four different choices. All of the changes were identified as increases in muscle activity. As expected, there was no change during the weight acceptance phase, except for the increase in the right gastrocnemius activity during the medial adjustment for the real condition. Most of the changes occurred during the pull-off and late swing, but they were not quite consistent between conditions. A change that was consistent between conditions was observed for the gluteus medius for the lateral adjustment. In addition, two changes were consistent within condition. First, there was a consistent increase in left gastrocnemius for the real condition for lateral and medial adjustments. Second, there was an increase in left tibialis anterior activity for the virtual condition for the same adjustments. For the short adjustment in the virtual condition no change in muscle activity was found. For the long adjustment, there was a consistent increase in left tibialis anterior activity during the push-off phase, but all other changes were different.

*Table 2*. Changes in muscle activation for both virtual and real conditions in each stride phase. Arrowhead pointing up indicates an increase in muscle response and vice-versa for arrowhead pointing down. Muscle changes that are bolded indicate similar changes in the virtual and real conditions for the respective stride phase. R and V letters after the obstacle position number stands for real and virtual conditions, respectively. L and R letters before the muscle code stands for left and right sides, respectively. (TA: tibialis anterior; GA: gastrocnemius; RF: rectus femoris; BF: biceps femoris; AL: adductor longus; GM: gluteus medius; ES: erector spinae)

| Choices | Stride Phases | | | |
|---|---|---|---|---|
| | Weight Acceptance | Push-off | Pull-off | Late Swing |
| Lateral (P1R) | ----- | ----- | ↑LGA | ↑RTA, ↑RGM |
| Lateral (P1V) | ----- | ----- | ↑RGM | ----- |
| Lateral (P2R) | ----- | **↑LGM** | **↑RGM**, **↑LGM**, ↑LGA | ↑RTA, **↑RGM**, **↑LGA** |
| Lateral (P2V) | ----- | **↑LGM**, ↑LTA | **↑RGM**, **↑LGM**, ↑LTA | **↑RGM**, ↑LGM, ↑LBF, **↑LGA** |
| Medial (P3R) | ↑RGA | ↑RES | ↑LES, ↑LGA | ↑RGM, **↑LES** |
| Medial (P3V) | ----- | ----- | ↑RAL, ↑LTA | **↑LES** |
| Short (P4R) | ----- | ----- | ↑RBF | ----- |
| Short (P4V) | ----- | ----- | ----- | ----- |
| Long (P6R) | ----- | ↑RAL, **↑LTA** | ↑RBF, ↑RGM, ↑LES, ↑LBF | ----- |
| Long (P6V) | ----- | ↑LGM, **↑LTA** | ----- | ↑RTA, ↑LBF, ↑LTA |

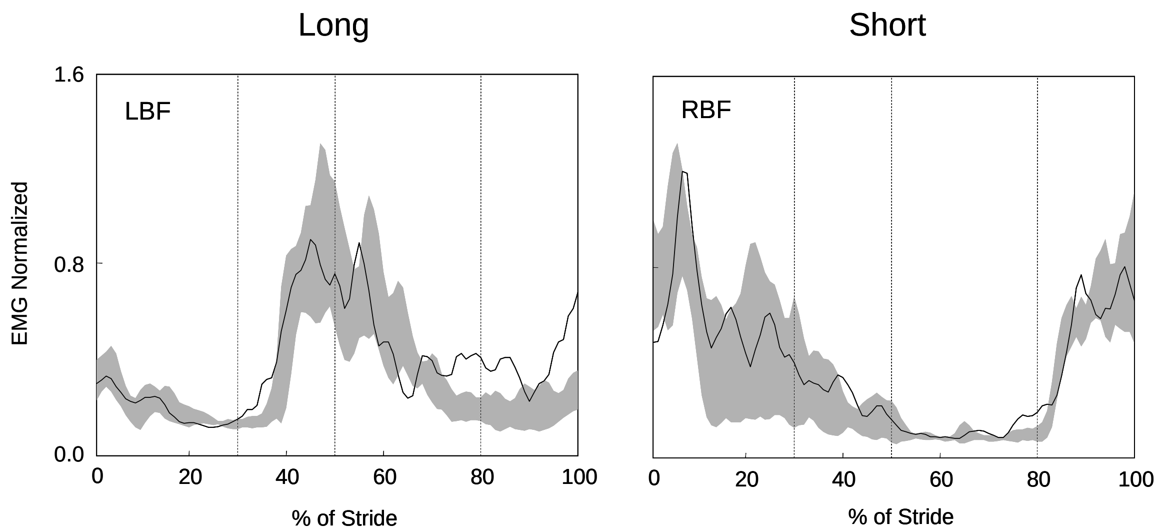


*Figure 10*. Ensemble average EMG profiles (from right heel contact on the trigger mat to right heel contact of the alternate foot placement) for WT (shaded area) and long (continuous line – left side) and short (continuous line – right side) adjustments. For the long adjustment, left biceps femoris (LBF) is shown; whereas for the short adjustment, right biceps femoris (RBF) is shown. Shaded area corresponds to the mean ± 1 standard deviation for the WT data. Vertical dashed lines indicate the four different phases of analysis: 1% - 30% (weight acceptance), 31% - 50% (push-off), 51% - 80% (pull-off), and 81% - 100% (late swing). For the long adjustment, there is an increase in LBF activity during pull-off and late swing phases. For the short adjustment, there is an increase in RBF activity during the end of pull-off phase.

## Discussion

In the present study we could systematically assess the validity of using a virtual planar obstacle as representative of a real irregular terrain. By validating this paradigm, future studies using virtual obstacles can be designed to assess different aspects related to the planning and implementation of alternate foot placement. In addition, measurement of muscle activity allowed us to directly assess the validity of the economy determinant in selecting alternate foot placement. The intentional decision and online control of stride modulation is a critical aspect involved with adaptation for cluttered terrains. We were able to methodically assess the changes in muscle activity by monitoring a large number of muscles related to changes in stride length and width while subjects walked on the ground. This study is the first to address stride length/width modulation following the participants' own selection of the preferred change. The discussion is organized to cover the three purposes of the present study.

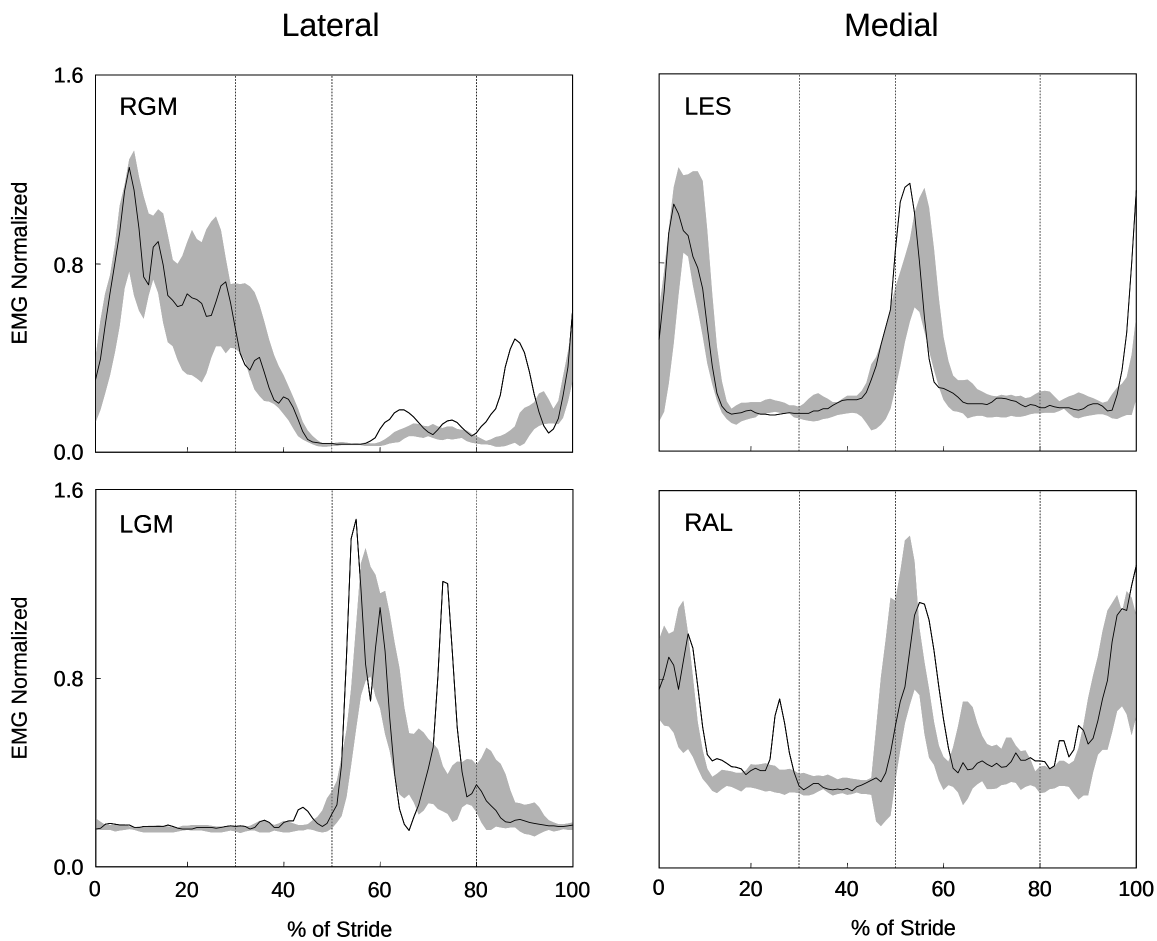


*Figure 11*. Ensemble average EMG profiles (from right heel contact on the trigger mat to right heel contact of the alternate foot placement) for WT (shaded area) and lateral (continuous line – left side) and medial (continuous line – right side) adjustments. For the lateral adjustment, right and left gluteus medius (RGM and LGM) are shown; whereas for the medial adjustment, left erector spinae (LES) and right adductor longus (RAL) are shown. Shaded area corresponds to the mean ± 1 standard deviation for the WT data. Vertical dashed lines indicate the four different phases of analysis: 1% - 30% (weight acceptance), 31% - 50% (push-off), 51% - 80% (pull-off), and 81% - 100% (late swing). For the lateral adjustment, there is an increase in RGM activity during pull-off and late swing phases and an increase in LGM during pull-off phase. For the medial adjustment, there is an increase in LES and RAL activities during pull-off and late swing phases.

*Alternate foot placement selection is not different between real and virtual conditions*

No statistically significant difference was found between real and virtual conditions for the dominant choice and foot placement variables. The only exception was found in step N-1, where foot placement modification vector magnitude and orientation were different between conditions. This difference is probably not of great relevance since the relative adjustment analysis identified a small contribution by step N-1 to the final alternate foot placement. The variables associated with all three determinants were also unaffected by the conditions. Maintenance of forward progression, stability, and foot displacement were not different between the real and virtual condition. In general, behaviorally there is no difference between real and virtual conditions. Therefore, the presence of the virtual planar obstacle can be used as an analog for the real environment to investigate alternate foot placement planning and selection process.

*Preference for minimizing foot displacement is economy-related*

For five of the obstacles (P1, P2, P3, P4, and P6) used in the current experiment, the dominant choice was the one that resulted in minimizing foot displacement from its landing position. The dominant choice coincided with the minimal value of the PMFD. The only exception was observed for the long choice in the P5 obstacle. For this particular obstacle, short adjustment would result in the minimal PMFD, but long choice was the dominant one. The long choice resulted in the second minimal PMFD and the difference between long and short PMFD was equal to 2.4 cm. Greig et al. (2004) found that the switch from long to short adjustments occurred only when the long adjustment resulted in a foot displacement larger than 7 cm compared to the short adjustment. Since the actual difference is less than 7 cm, it is possible that there is a threshold for switching from long to short adjustments. This threshold can be economy and/or stability related. Future studies should address this issue.

Foot placement modification vector magnitude was just slightly larger than the PMFD. The overall mean difference was equal to 4.4 cm. Thus, participants were placing the foot just past the edge of the obstacle as shown by Moraes et al. (2004). This clearly supports the idea that people effectively minimize the foot displacement from its normal landing spot when avoiding an obstacle. It was suggested that minimization of foot displacement is economy related (Patla et al. 1999). Converging evidence suggest that movements in general and during locomotion in particular, are planned to minimize the associated metabolic cost. For example, metabolic cost is diminished for the preferred step length and width (Cavanagh and Williams 1982; Donelan et al. 2001, 2002). Also, when learning a new task, metabolic cost diminishes with practice (Lay et al. 2002). In addition, during development metabolic cost associated with walking and running diminishes with increase in age (Morgan et al. 2004), and at a speed higher than 2 m/s people prefer to run than to walk since it is more economical (Alexander 2002). Thus, when adapting gait to environmental challenges it is reasonable to suppose that people would prefer the options that minimize the metabolic cost. The strong bias towards minimizing energy cost is probably a result of the evolution process (Alexander 2002).

The results of the regression analysis between PCTMA and foot placement modification vector magnitude show that increase in foot displacement is associated with increase in muscle activity. Therefore, when minimizing the amount of foot displacement, participants are also minimizing the changes in the ongoing muscle activity. Since there is a good relationship between muscle activation and oxygen uptake (Henriksson and Bonde-Petersen 1974; Kyröläinen et al. 2001; Millet et al. 2002; Praagman et al. 2003; Sengupta and Das 2004), it is proposed that the decrease in muscle activation observed with the decrease in foot displacement decreases the metabolic cost associated with the movement. The small variability explained by the PCTMA may be a result of the number of muscles monitored. Although the number of muscles monitored in the present study is quite high, it is still not as high as the number of muscles involved with the locomotor behaviour. Indeed, Winter (1991) has catalogued the EMG activity of 25 muscles (50 bilaterally) during gait, not including the upper limb and deep muscles. Clearly, much more than the seven muscles (14 bilaterally) are recruited during gait. Ideally, it would be more representative to monitor a larger number of muscles, however that is not a simple task. Therefore, the use of a representative muscle from each of the major muscle groups proved to be sufficient to show the relationship between changes in muscle activity and foot displacement. If it would be possible to include more muscles in this analysis, the variability explained by PCTMA would be higher and the precision of the estimate would be improved. The fact that the intercept was not different from zero is an indication of the robustness of the PCTMA since as expected maintenance of normal foot placement would result in no change in muscle activity.

*Implementation of the alternate foot placement is muscle- and phase-specific in the ipsi- and contralateral sides*

The major changes in EMG activity occurred after left heel contact with the ground. This was clearly reflected in the values of the relative adjustment for step N-1. The lateral adjustment, which mainly resulted in modulation of step width, was achieved by increasing the activity of the right hip abductor during pull-off and late swing as proposed by Patla (1991). The enlargement of the foot displacement created an additional contribution of the left hip abductor, but only at the push-off and pull-off phases. This shows that changes are muscle and phase-specific for the ipsi- and contralateral muscles as proposed by Patla et al. (1989b). The additional contribution of the left gluteus medius resulted in tilting the pelvis downward on the left, since the left foot was on the ground during these two phases, facilitating the right lower limb to be displaced to the right, therefore reducing the need for a much stronger activation of the right gluteus medius, which would create a larger destabilizing moment. The increase in right gluteus medius activity was probably related to properly landing the foot at the edge of the obstacle. For the real condition, there was an increase in the right tibialis anterior activity during the late swing. This increase in ankle flexion during swing may have delayed the foot landing (Varraine et al. 2000), contributing to enlarging step duration. Indeed step duration was statistically greater (not reported) for the real condition compared to normal walking (P1 = 0.56 s; P2R = 0.56 s; WT = 0.53 s). The increase in left biceps femoris activity for the virtual condition during late swing may be seen as a compensation for the increase in left gastrocnemius during the same phase. This increase in left biceps femoris stabilizes the pelvis and prevents a substantial increase in the trunk forward velocity.

It was hypothesized that the medial adjustment, which narrows the step, was implemented mainly by the hip adductors. However, the expected increase in the adductor longus activity was only consistently observed in the virtual condition during the pull-off phase. In both conditions, there was a consistent increase in left erector spinae during late swing. For the real condition this increase is more pronounced as it appears also during the pull-off phase. It is possible that the increase in left erector spinae contributes to the passive movement of the leg more medially. This increase in the left erector spinae activity may twist the trunk facilitating the leg movement medially. Since the increase is more pronounced for the real condition, there may be no need for substantial increase in adductor longus involvement and the right gluteus medius may eccentrically control foot landing during late swing. Patla and Prentice (1995) have described the passive control mechanisms of subjects who walked over obstacles. They demonstrated that the increase in hip and ankle flexion was achieved through passive forces induced by translational action at the hip and rotational action at the knee joint. This clearly shows that the central nervous system (CNS) takes advantage of the intersegmental dynamics in order to properly control adaptive movements.

For both lateral and medial adjustments, consistent increases were found in the left gastrocnemius and tibialis anterior activity during the pull-off phase for the real and virtual conditions, respectively. Gastrocnemius activity at the push-off phase has been shown to be greatly related to forward propulsion (Winter 1991; Gottschall and Kram 2003). Although not reported, $T_{COM}$ velocity in the AP direction was statistically greater for the real condition than for the virtual condition. Thus, the increase in gastrocnemius activity was used to increase $T_{COM}$ velocity in the AP direction for the real condition since it enhances the left limb push-off (the stride phases presented in Table 2 are based on right limb events). However, there was no significant difference between real and virtual conditions for the $T_{COM}$ velocity in the AP direction for the P2 obstacle. This was probably because of the late increase in left gastrocnemius observed for the virtual condition during the late swing. On the other hand, the increase in left tibialis anterior activity for the virtual condition is unclear.

For the short adjustment in the real condition, there was an increase in right biceps femoris during the pull-off phase. Although the pull-off phase combines the end of the stance and the early portion of the swing, the changes for the right biceps femoris occurred mainly towards the end of the pull-off phase for the short adjustment. This increase helps in decelerating the swing leg, stopping the pendular leg movement so that the foot landed earlier than it would have spontaneously (Varraine et al. 2000). The result of this mechanism is the reduction in step duration. In fact, step duration was reduced for the short adjustment, although these results are not reported here. No change in muscle activation was observed for the virtual condition. It is possible that because the stride length regulation was small (~9.0%), the changes in muscle activity for implementing the short adjustment were within the variability for the normal walking. Varraine et al. (2000) have reported changes in stride length slightly greater (12.1%). This hypothesis is reinforced by the reduction in the $T_{COM}$ AP velocity for the short virtual adjustment compared to normal walking in both steps (i.e., N-1 and N), whereas for the short real adjustment the only difference occurred in step N. The larger $T_{COM}$ AP velocity for the real condition compared to the virtual condition may be a consequence of the increase in leg braking without a compensatory mechanism for the trunk. However, this does not affect the $T_{COM}$-BOS relationship and therefore it is probably within an acceptable range of variation by the CNS.

For the long adjustment, a systematic increase in left tibialis anterior during push-off was observed for both conditions. During this phase the left limb is at late swing and during this period the tibialis anterior activity keeps the foot dorsiflexed during the reach phase (Winter 1991). This increase enhances ankle dorsiflexion and helps in lengthening the step, as proposed by Varraine et al. (2000). For the real condition there was a bilateral increase in biceps femoris activity during the pull-off phase. In opposition of what happened to the short adjustment, the increase was located more at the beginning of the pull-off phase or during the late stance. The increase in right biceps femoris activity during late stance, which was previously reported by Patla et al. (1989b) and Varraine et al.

(2000), increases the push-off action via action at the hip. The increase in the left biceps femoris enhances the support against gravity, since the major changes occurred around mid-swing of the right limb. Although the increase in left biceps femoris was located at late swing, it occurred mainly on the initial part of the late swing, which is also near to the mid-swing, and therefore it increases the body support. Varraine et al. (2000) and Patla et al. (1989b) have also reported increases in triceps surae activity during push-off. The failure to repeat this finding is possibly related to the smaller change in step length in the present study (10.0% versus 18.8%). For both virtual and real conditions, an increase in gluteus medius was observed in different phases. The meaning of such changes is not completely clear. Greig et al. (2004) have reported that the long adjustment also resulted in some increase in step width. Perhaps the increase in gluteus medius is related to such a mechanism. In the present study an increase of 5.5% in step width was found for the virtual condition. However, no increase in step width was found for the real condition. The increase in the right adductor longus and left erector spinae activities may have compensated for the gluteus medius increase and kept the step width unaltered. The increase in the right tibialis anterior activity during the late swing was also observed by Varraine et al. (2000). This increase maintains the ankle flexed during lengthening so that the foot landed later and, thus, farther.

In summary, the changes in muscle activity are quite complex and diverge from some previous work and also between conditions. The differences observed for alternate foot placement implementation indicate the control system has some flexibility to make the necessary changes in order to achieve the same goal. The absence of triceps surae involvement in step lengthening is an indication that this muscle group is only requested during large changes. The increase in step width for the P2 obstacle created the necessity of incorporating the left gluteus medius for proper achievement of the goal. These two examples clearly show that the control mechanisms are muscle- and phase-specific, based on the demands of the task.

*Summary*

This study has shown that the virtual planar obstacle paradigm is appropriate for research involving alternate foot placement selection and planning. The present study also provided validation for the economy assumption behind the minimum foot displacement determinant. Preference for minimizing foot displacement is economy-related.

# Chapter 3

# Validating determinants for alternate foot placement selection algorithm during human locomotion in a cluttered terrain

## Introduction

Alternate foot placement selection during locomotion in cluttered environments cannot be exclusively sensory-driven (Patla et al. 1999; Moraes et al. 2004). Vision and proprioceptive inputs provide information about undesirable landing spots in the pathway and the amount of foot displacement in each direction relative to the normal landing position necessary to avoid them. However, when more than one option exists for minimizing foot displacement, vision and proprioceptive inputs alone are not enough to help determine where to step. It has been shown that the selection of alternate foot placement is based on three determinants: minimum foot displacement (i.e., economy), stability, and maintenance of forward progression (Patla et al. 1999; Moraes et al. 2004). When only one option offers the minimum foot displacement from its normal landing spot, it is the preferred choice. However, often the amount of foot displacement is similar for more than one option. In this case, two additional rules apply. If the minimum foot displacement from its normal landing spot is the same for one adjustment in the frontal plane and for another in the plane of progression, the preference is to make the adjustment in the plane of progression (Patla et al. 1999). If the minimum foot displacement is the same within the same plane of movement, the preferred choice is long (i.e., lengthening the step) in the plane of progression and medial (i.e., narrowing the step) in the frontal plane (Patla et al. 1999).

Moraes et al. (2004) recently validated the primacy of minimum foot displacement in determining the alternate foot placement choice. In this study, the predicted minimum foot displacement for each combination of options (i.e., long, short, lateral, and medial) and obstacle position was calculated based on the average foot placement during normal walking. The dominant choice minimized the foot displacement from its normal landing position for majority of the cases, therefore validating minimum foot displacement as one of the determinants used for alternate foot placement selection. The other two determinants (i.e., stability and forward progression) have not yet been addressed and, consequently, validated. This is one of the focuses of the present study.

During walking, stability maintenance is a dynamic process due to continuous changes in the BOS and COM location. Walking is a cyclical sequence of falling forward and recovering balance by properly placing the swing foot, which determines the future location of the center of pressure (Patla 2003; Redfern and Schumann 1994; Winter 1995). This suggests that COM location relative to the BOS is a good indicator of body balance during walking. This measure of stability has been extensively used in studies involving insects (see Ting et al. 1994) where it is appropriate to consider static measure of stability since they usually have more than two legs on the ground. During single support, COM projection is outside the BOS in both anteroposterior and mediolateral directions. Since at each heel contact balance is re-established by proper foot placement, it is appropriate to measure dynamic stability during double support phase. Thus, in the present study, COM projection relative to the BOS during the beginning of double support phase is used to assess stability.

However, only distance parameters may not be adequate to assess dynamic stability. During walking, the dynamics of the body play an important role and this can be captured by combining COM position and velocity (Pai and Patton 1997; Iqbal and Pai 2000). More recently, Hof et al. (2005) have proposed a simple and elegant calculation that captures the contribution of COM velocity to dynamic stability, which generates similar predictions as proposed by Pai and Patton (1997). They used the current location of COM and its velocity to extrapolate COM position. This extrapolated COM position can then be compared against the maximum reach of center of pressure in order to identify whether or not the system is stable. Therefore, in addition to the COM-BOS distance, another measure of stability was taken by computing the distance between the extrapolated COM position and the limit of the BOS, which is called margin of dynamic stability. Furthermore, Patla (2003) has shown that more than one step is needed to completely overcome the instability generated by different sources of perturbation. During the alternate foot placement task, balance may be compromised since there are substantial changes in foot placement location. Therefore, in order to unequivocally validate the stability determinant it is necessary to assess the COM-BOS relationship and the margin of dynamic stability not only in the adaptive step, but also in the subsequent step.

The preference for changes in the plane of progression over changes in the frontal plane has been attributed to maintenance of forward progression (Patla et al. 1999). More recently, Moraes et al. (2004) proposed that when making changes in the frontal plane, people try to move the foot not only medially, but also forward in order to minimize deviation from the forward goal. Although this foot displacement reveals partially supports the maintenance of the forward progression determinant, more global measures of body trajectory are needed. Maintenance of forward progression is best assessed by examining COM trajectory.

Experimentally, this study introduces a new manipulation through a forced condition that 1) removes the selection and planning component of alternate foot placement, and 2) provides non-dominant foot placement choices for all participants for analyses. In the forced condition, participants are visually cued to select one foot placement option. This allows the evaluation of how the planning component impacts the alternate foot placement performance. Since there is a dominant response for each obstacle when allowed to choose, the forced condition fills the gaps with non-dominant choices. Thus, the purpose of this study is to validate both stability and forward progression determinants when selecting alternate foot placement and when foot placement is cued. It is hypothesized that these two determinants will have a major influence on selection and execution of alternate foot placement.

## Method

### *Participants*

Eight participants volunteered for this study (4 F and 4 M; age 25.4 ±4.7 years; height 1.75 ±0.10 meters; mass 69.5 ±6.7 kilograms). Participants did not report any neurological, muscular, or joint disorders that could affect their performance in this study. The Office of Research Ethics at the University of Waterloo approved the procedures used in this study.

### *Protocol*

Participants were asked to walk on level ground at a self-selected pace on a pathway containing a force plate (AMTI, Boston, USA) and an embedded liquid crystal display (LCD) monitor (Samsung SyncMaster™ TFT 181T Black) (Figure 1). A piece of Plexiglas™ was placed over the LCD monitor so that participants could step normally on it. The starting point was adjusted for each participant in order to ensure that the entire left foot landed on the force plate and the subsequent right foot landed on the centre of the screen. Participants were required to avoid stepping with the right foot on a virtual white planar obstacle that would be displayed in the LCD screen. The obstacle appeared at left heel contact (HC) on the force plate (vertical component larger than 5 N), which provided one step for implementing the alternate foot placement. The pathway was covered with a black rubber carpet that had specific cuts to accommodate the force plate and the LCD monitor. The force plate was also covered with the same black rubber carpet. The monitor edge was also black. For the trials with no obstacle, the screen background was kept completely black. One obstacle labelled mediolateral (ML) was designed to facilitate adjustments in the frontal plane; the other obstacle labelled anteroposterior (AP) produced foot placement in the sagittal plane. Obstacles were displayed in the middle of the screen. Participants performed the task under two conditions: free and forced. In the free condition, participants chose the alternate foot placement that was more appropriate for avoiding the planar obstacle. In the forced condition, a green arrow projected over the white planar obstacle indicated the direction in which the alternate foot placement must be performed (Figure 1). The white obstacle and the green arrow were displayed simultaneously at left HC on the force plate. For the AP obstacle, two forced conditions were used: long and short. For the ML obstacle, two forced conditions were used: medial and lateral. Therefore, a total of six conditions were collected: AP free, ML free, long forced, short forced, lateral forced, and medial forced. Six trials were collected per condition (36 trials). In order to keep a probability of obstacle appearance equal to 20%, 144 walk-through (WT) trials were also collected. Trials were completely randomized.

Twenty-four infra-red emitting diodes (IREDs) were placed bilaterally on the following anatomical landmarks: 5$^{th}$ metatarsal, heel, lateral malleolus, femur head, greater trochanter, anterior superior iliac spine, iliac crest, lower rib, greater tubercle of humerus, elbow axis, ulnar styloid, and ear. One more IRED was placed at the xiphoid (Figure 1).

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. The three components of the ground reaction forces and moments under the stance limb (i.e., left limb) were also collected with the same force plate used to trigger the obstacle display at a sampling rate of 120 Hz. At the end of the experimental session, feet were traced on a sheet of paper for posterior measurement of the foot length and width used in the calculation of the predicted minimum foot displacement. Participants were videotaped while performing the task.

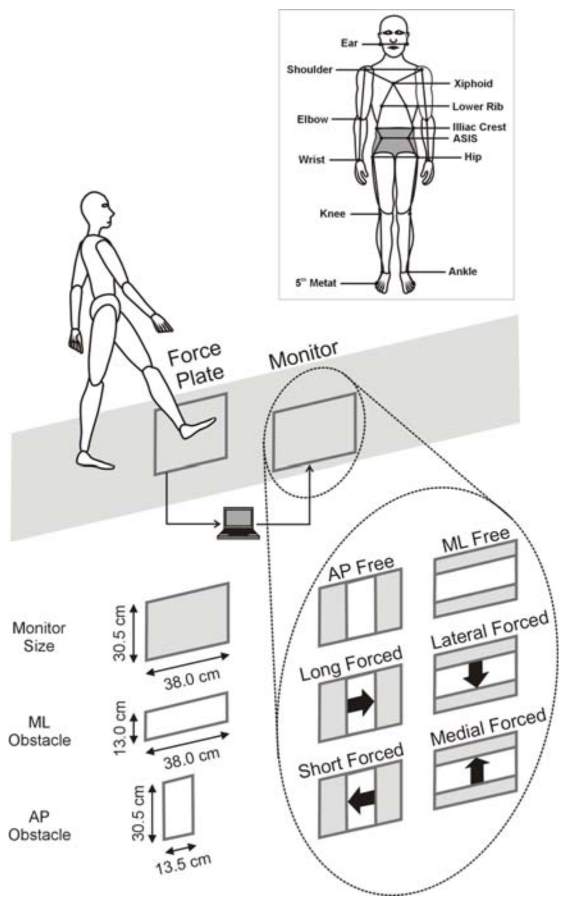


*Figure 1*. Experimental setup showing the force plate and the LCD monitor. The pathway appears in grey instead of black for esthetical reasons and the arrows appear in black instead of green. Top right corner shows the marker placement of the 25 IREDs (see text for specific location of the markers). Bottom part shows the dimensions of the monitor and the planar obstacles used as well as the six experimental conditions.

*Data analysis*

Videotapes were used to identify the successful trials for all the adjustments in the forced condition. In addition, in the unsuccessful trials the errors were classified as follows: wrong adjustment, stepped on the obstacle, and others. Wrong adjustments are the trials where one adjustment was requested and the participant made some other adjustment. Others are trials in which participants missed the force plate, terminated gait just before or after the obstacle, or simply did not see the obstacle at all. The percentage for each of these parameters was calculated based on the total number of trials across subjects.

Marker coordinates were filtered using a fourth-order zero lag low-pass digital Butterworth filter with a cut-off frequency of 6 Hz. A model with 16 segments was used to calculate whole body COM position: feet, legs, thighs, arms, forearms, head, pelvis, and trunk modelled with four components (Winter 2005). Anthropometric parameters were obtained from Winter (2005). COM velocity was calculated as the first derivative of COM position (central difference procedure). HC was determined by visual inspection of the foot stick figure using the OptoFix software (Mishac Kinetics, Waterloo, Ontario, Canada). Estimation of HC based on the vertical component of the force plate ($F_y > 5$ N) was used as the gold standard in order to validate the visual inspection. Differences between these two methods were always within the range of 2 frames (i.e., 0.03 s).

Ankle markers (i.e., lateral malleolus) were defined as the limb end-point and used to calculate the foot placement modification vector (Figure 2). For each experimental trial, relative coordinates (RCs) were computed as the subtraction of the ankle coordinates of the trial (x and z) from the average coordinates of the WT trials at HC. The average values were obtained from 20 randomly selected WT trials. The RCs were used to calculate the foot placement modification vector magnitude and foot placement modification vector orientation (i.e., angle). Vector orientation was used to define the adjustment made in the free condition. Classification included four directions of adjustment: lateral (0° - 45° and >315° - 360°), long (>45° - 135°), medial (>135° - 225°), and short (>225° - 315°). Percentage of adjustment in each direction was calculated relative to the total number of trials successfully performed by all the participants. The same vector analysis performed for the lower limb end-point was performed for the COM at HC. The cosine of the absolute difference between foot and COM foot placement modification vector angle was used to identify whether or not foot and COM movement vector direction were oriented in the same direction.

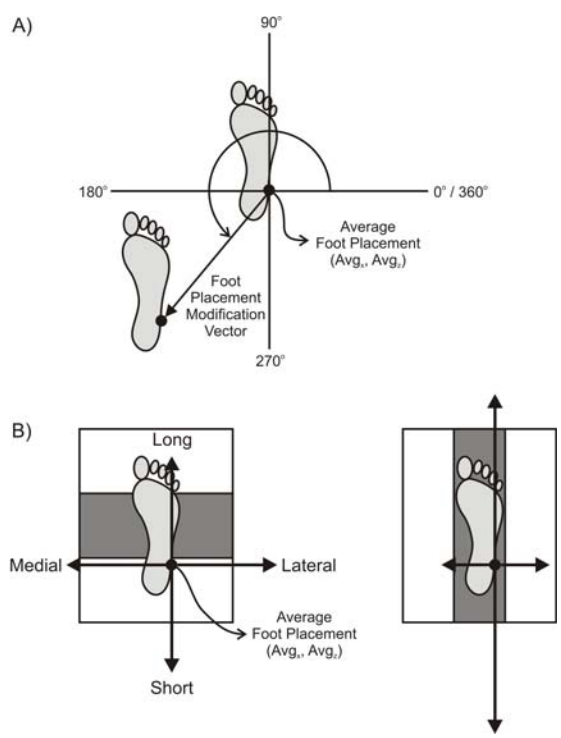


*Figure 2.* A) It shows the foot placement modification vector for a hypothetical choice in the third quadrant. Foot placement modification vector magnitude is calculated as the distance between average foot placement and alternate foot placement. Foot placement modification vector angle is defined relative to average foot placement. B) It shows the predicted minimum foot displacement needed to clear the obstacle in four directions for both obstacles. The magnitude of the arrow indicates the amount of necessary foot displacement.

The right ankle marker velocity profile was used to determine the onset of change in limb trajectory in the AP and ML directions. Velocity data were aligned based on left HC on the force plate, since this was the trigger for obstacle appearance. For each experimental trial, adjustment onset was defined as the first deviation of the velocity profile from the variability range around the mean for the WT trials. For the ML direction, variability was defined as one standard deviation whereas for the AP direction two standard deviations were used (see left side of Figure 4). This difference is based on the fact that the variability is much smaller in the AP direction than in the ML direction.

Right foot markers ($5^{th}$ metatarsal, lateral malleolus, and heel) and mean data from both feet tracings (foot length and width) were used in calculating the predicted minimum foot displacement (PMFD) for each option and obstacle (Figure 2). PMFD is defined as the perpendicular distance relative to each side of the obstacle necessary to clear it and to land the foot just at the edge of the obstacle.

At HC, feet markers (right and left $5^{th}$ metatarsal and heel) were used to define the BOS. Based on the vertical projection of the COM and BOS location, the AP and ML distances of the COM in relation to BOS were computed (see Figure 10 for illustration). In the AP direction, positive values indicated that COM was ahead of the anterior margin of the BOS and vice-versa for negative values. COM-BOS AP distance in relation to the posterior margin of the BOS was also calculated and it was used, combined with the distance relative to the anterior margin, to determine the COM location (i.e., inside, behind, or ahead of the BOS). For the adaptive step (step N), ML distance was calculated relative to right heel marker whereas for the subsequent step (step N+1), ML distance was calculated relative to left heel marker. In the ML direction, positive values indicated that COM was medial relative to foot and within BOS and vice-versa for negative values.

COM-BOS distance calculation includes essentially spatial parameters. However, during walking, COM displacement velocity also has to be considered when defining stability. Therefore, an additional stability parameter was calculated incorporating COM velocity. This parameter was based on the work done by Hof et al. (2005). According to these authors, COM location can be extrapolated based on its actual velocity as follows:

$$\mathrm{XcoM} = \mathrm{COM} + \frac{\dot{\mathrm{COM}}}{\omega_0} \qquad \text{Equation 1}$$

where XcoM is the extrapolated center of mass position, COM is the actual center of mass position, $\dot{\mathrm{COM}}$ is the velocity of the center of mass, and $\omega_0$ is defined by Equation 2:

$$\omega_0 = \sqrt{\frac{g}{\ell}} \qquad \text{Equation 2}$$

where g is the acceleration due to gravity and $\ell$ is the length of the inverted pendulum (in our analysis we used the height of the COM).

Based on the XcoM, margin of dynamic stability (MDS) was calculated at HC as follows:

$$\mathrm{MDS} = \mathrm{BOS}_{max} - \mathrm{XcoM} \qquad \text{Equation 3}$$

where $\mathrm{BOS}_{max}$ is the limit of the base of support. Fifth metatarsal and heel markers were used to define $\mathrm{BOS}_{max}$ in the AP and ML directions, respectively. For step N (i.e., adaptive step), calculations were made relative to right foot; whereas for step N+1, calculations were made relative to left foot. Since velocity polarity changes from step-to-step in the ML direction, Equation 3 was rearranged for MDS calculation for the left foot ($\mathrm{MS} = \mathrm{XcoM} - \mathrm{BOS}_{max}$). A positive value for MDS indicates that XcoM is within BOS and, therefore, the system is dynamically stable and vice-versa for negative values.

Maintenance of forward progression was estimated as the COM deviation relative to the straightforward direction of locomotion. This variable was calculated as the angle between the straightforward direction, which is parallel to the AP axis, and the line connecting the COM location at HC in steps N and N+1. Positive changes indicate a deviation to the right whereas negative changes indicate a deviation to the left.

The following step parameters were calculated: step length (SL) and step width (SD). SL was defined as the difference of the x coordinate between two consecutive heel-contacts. SW was defined as the difference of the z coordinate between two consecutive heel-contacts. For the SW, negative values indicate the presence of a cross-over between right and left limbs. Percentage of cross-over was calculated as a proportion to the total number of trials for each condition.

Force plate data were used to calculate braking and propulsive impulses in three directions (AP, ML and Vertical). The transition between braking and propulsive impulse was defined by identifying the zero crossing point in the AP component of the ground reaction force (Figure 5). Braking impulse was obtained by computing the area under the curve from HC to zero-crossing whereas propulsive impulse was defined as the area from zero-crossing to toe-off (vertical component smaller than 5 N).

*Statistical analyses*

For the onset of limb trajectory change, impulse and maintenance of forward progression, one-way ANOVAs (Condition) with repeated measures were carried out. For the PMFD, a one-way ANOVA (Option) with repeated measures was performed for each obstacle position. For the remaining dependent variables, two-way ANOVAs (Condition X Step) with repeated measures in both factors were carried out. For each dependent variable, the mean value was calculated per participant and used in the statistical analyses. Medial free condition was not used for any statistical analyses because only four participants had freely chosen this adjustment. Means and standard deviations of these four participants are shown in the graphs for illustrative purposes only. Because comparisons between long/short and lateral/medial were not of interest, analyses were divided into two groups: medial/lateral and long/short conditions. For the long/short conditions, analyses were split because one participant never freely chose to shorten the step for the AP obstacle. Therefore, four ANOVAs were carried out: 1) conditions (long forced and short forced) X step; 2) conditions (long free and short free) X step; 3) conditions (long forced and long free) X step; 4) conditions (short forced and short free) X step. Alpha value was set to 0.05. When main or interaction effects were found, Least Squares Means post-hoc was used to identify which treatments differ from one another.

**Results**

*What is the dominant choice in the free condition?*

For the AP obstacle, the dominant choice was the long adjustment (Figure 3). For the ML obstacle, the dominant choice was lateral. Both choices were preferred in more than 50% of the trials.

*Are the participants successful in performing the forced condition?*

For the forced condition, the highest success rates for the AP and ML obstacles were also observed for long (89.1%) and lateral (79.2%) adjustments, respectively (Figure 3). The success rates for short and medial adjustments in the forced condition were equal to

47.9% and 52.1%, respectively. The highest rates for wrong adjustments were observed for short (41.7%) and medial (29.2%) adjustments, which were not the preferred adjustments in the free condition. For the short forced condition the wrong adjustment was dominantly long (95%). The wrong adjustment in the medial forced condition was more distributed, with a higher percentage for lateral (50%), followed by long (28.6%) and short (21.4%) adjustments. In addition, 36.4% of the successful trials involving short forced adjustments presented a backwards foot movement which is indicative that the original planning involved long adjustment, but because of the forced nature of the task participants needed to reverse foot trajectory to perform the task properly.

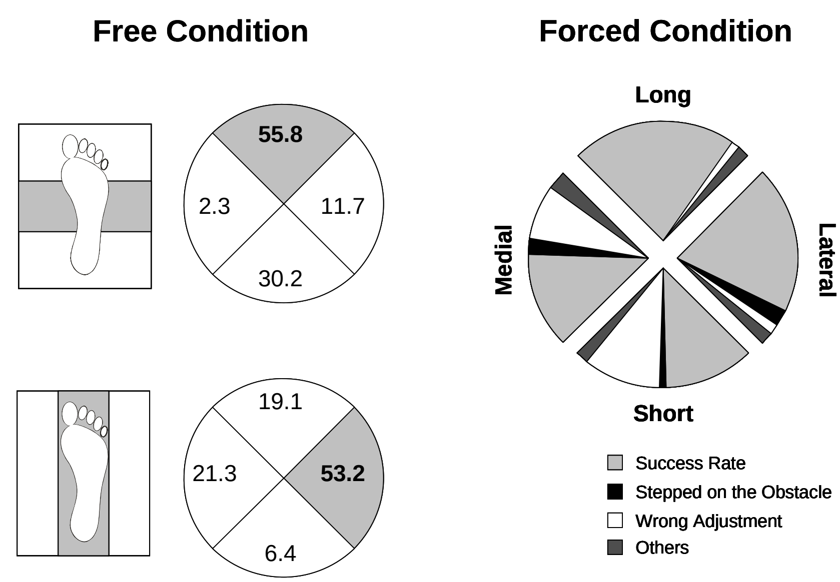


*Figure 3*. Left side shows the percentage of trials for each adjustment in the free condition. Shaded area indicates the preferred choice. Right side shows the success rate for the forced condition as well as the percentage of wrong adjustments, stepping on the obstacle, and others.

*Does the movement planning and initiation time bias the preferred alternate foot placement?*

One-way ANOVAs (Condition) with repeated measures identified a main effect of condition only for the comparison involving short forced and free adjustments ($F_{1,6} = 6.11$, $p = 0.0483$). As Figure 4 illustrates, short free adjustments started earlier than short forced adjustments.

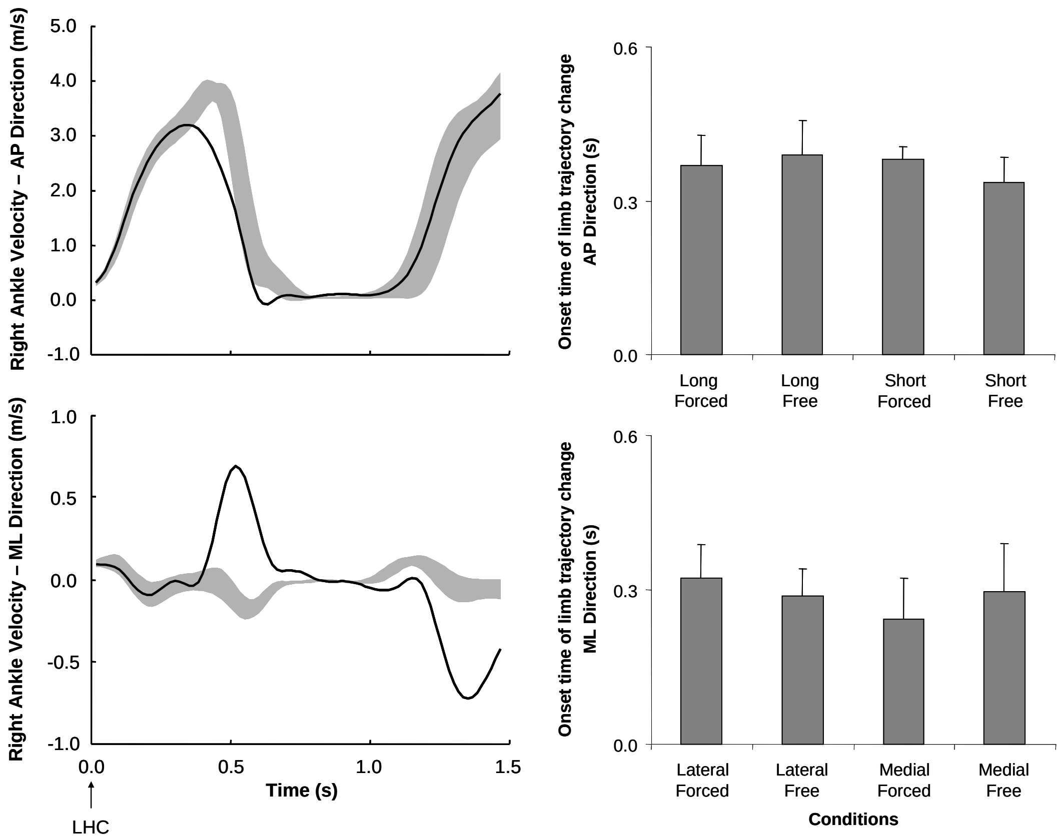


*Figure 4*. Time histories of the right ankle velocity on the left show the mean plus/minus two standard deviations (shaded area) for the AP direction and one standard deviation for the ML direction. One illustrative trial of a short forced condition (top) and a lateral forced condition (bottom) are also shown (solid line). The point where the solid line deviates from the shaded area was defined as the onset time of limb trajectory change. LHC stands for left heel-contact on the force plate, which was the trigger for the obstacle appearance. On the right, bar graphs show the means and standard deviations for the AFP onset for the long/short conditions (top) and lateral/medial conditions (bottom).

*Is the initial response to the appearance of the obstacle specific to the final foot placement or is it generic?*

The statistical analyses results for the impulses in all three directions are shown in

Table 1. Mean and standard deviation data for AP, ML, and vertical impulses are plotted in Figure 5.

*Table 1*. Output of the ANOVAs for the impulse variable. Probability values in italics indicate the presence of main/interaction effects.

| | | AP Direction | | ML Direction | | Vertical Direction | |
|---|---|---|---|---|---|---|---|
| Conditions | DF | F Value | Pr > F | F Value | Pr > F | F Value | Pr > F |
| Braking Impulse | | | | | | | |
| LonFo / ShoFo / WT | 2, 14 | 5.51 | *0.0172* | 2.71 | 0.1010 | 8.88 | *0.0032* |
| LonFr / ShoFr / WT | 2, 12 | 8.38 | *0.0053* | 2.30 | 0.1424 | 28.42 | <*.0001* |
| LonFo / LonFr / WT | 2, 14 | 4.01 | *0.0419* | 3.56 | 0.0561 | 5.00 | *0.0230* |
| ShoFo / ShoFr / WT | 2, 12 | 14.11 | *0.0007* | 1.78 | 0.2110 | 26.12 | <*.0001* |
| LatFo / LatFr / MedFo / WT | 3, 21 | 5.06 | *0.0086* | 8.68 | *0.0006* | 14.36 | <*.0001* |
| Propulsive Impulse | | | | | | | |
| LonFo / ShoFo / WT | 2, 14 | 101.96 | <*.0001* | 39.65 | <*.0001* | 29.65 | <*.0001* |
| LonFr / ShoFr / WT | 2, 12 | 70.99 | <*.0001* | 15.45 | *0.0005* | 73.89 | <*.0001* |
| LonFo / LonFr / WT | 2, 14 | 68.79 | <*.0001* | 9.68 | *0.0023* | 31.05 | <*.0001* |
| ShoFo / ShoFr / WT | 2, 12 | 32.68 | <*.0001* | 13.69 | *0.0008* | 27.64 | <*.0001* |
| LatFo / LatFr / MedFo / WT | 3, 21 | 9.77 | *0.0003* | 62.09 | <*.0001* | 4.43 | *0.0146* |

LonFo = long forced; LonFr = long free; ShoFo = short forced; ShoFr = short free; LatFo = lateral forced; LatFr = lateral free; MedFo = medial forced; DF = degrees of freedom

In the AP direction, braking impulse was larger for long (forced and free) and short (forced and free) adjustments than for WT. In the vertical direction, braking impulse increased for the short adjustments (forced and free) in comparison to WT and long adjustments (forced and free). Vertical braking impulse also increased for the long adjustments (forced and free) in comparison to WT. ML braking impulse was greater for the long forced adjustment than for the WT. The propulsive impulses in all three directions increased for the long adjustments and decreased for the short adjustments in comparison to WT. There was no difference between forced and free adjustments for both long and short adjustments.

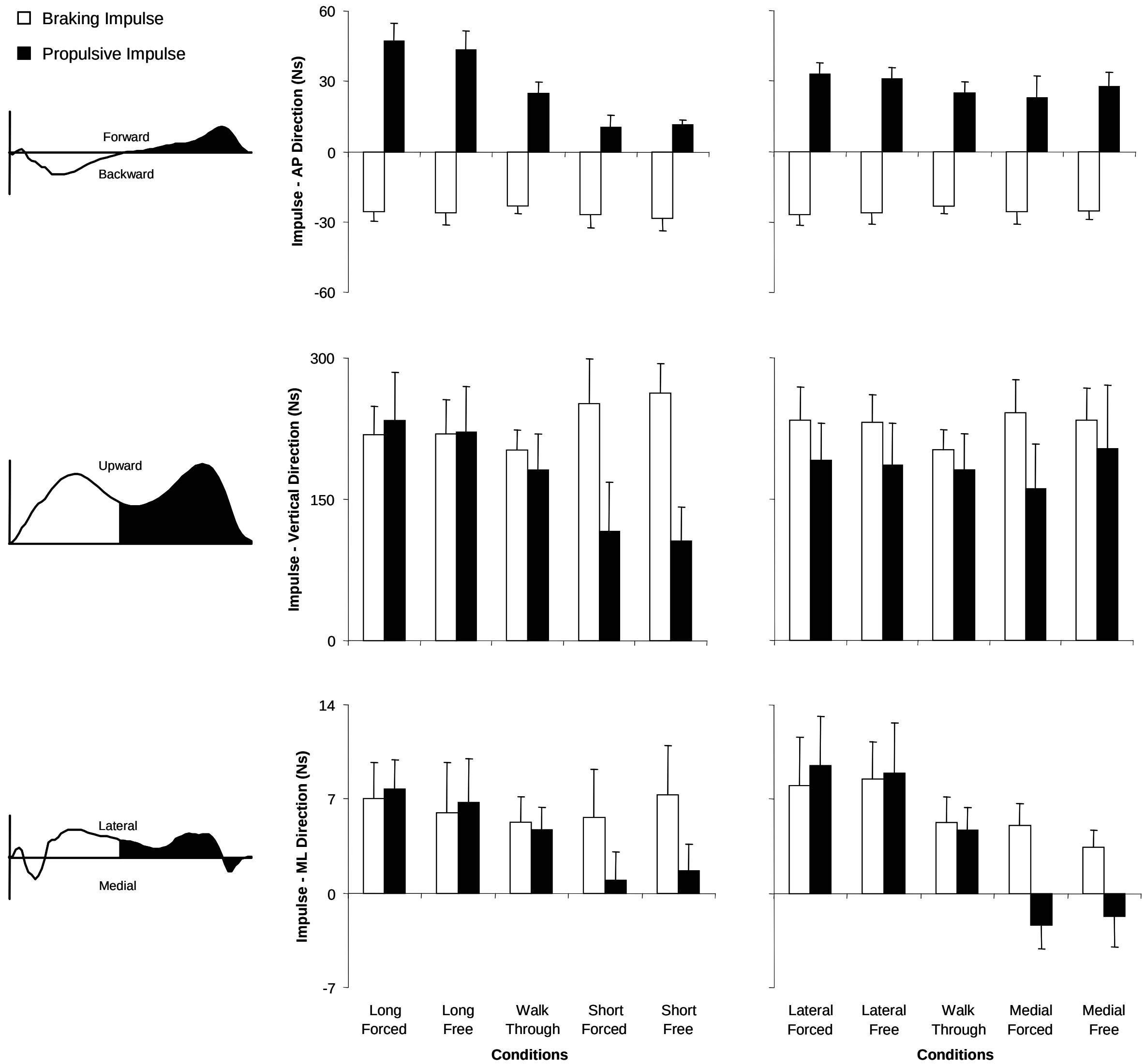


*Figure 5*. Mean and standard deviation for the braking (white bars) and propulsive (black bars) impulses in the AP direction (top row), vertical direction (middle row), and ML direction (bottom row) for the long/short (middle column) and lateral/medial (right column) adjustments. Ground reaction force-time curves are shown on the left column and they illustrate the area under each curve used to compute braking and propulsive impulses.

AP and vertical braking impulses were greater for lateral (forced and free) and medial adjustments than for WT. No difference was found between lateral and medial forced adjustments, as well as between lateral forced and free adjustments. In the ML direction, braking impulse increased for the lateral (forced and free) adjustments in comparison to WT and medial forced adjustment, which were not different from each other. Braking impulses for the lateral forced and free adjustments were not different from each other in all three directions. AP propulsive impulse was greater for the lateral adjustments (forced and free) in comparison to WT and medial forced adjustment, which were not different from each other. In the vertical direction, propulsive impulse was smaller for the medial forced adjustment than for the WT and lateral adjustments (forced and free), which were not different from each other. ML propulsive impulse increased for lateral adjustments (forced and free) and decreased for the medial forced adjustment in comparison to WT. No difference between lateral forced and free adjustments were found for any direction for the propulsive impulse.

*Is the minimum foot displacement different between choices in the sagittal and frontal planes?*

One-way ANOVAs (Option) with repeated measures were carried out for the PMFD for each obstacle separately. For the AP obstacle, a main effect of option was observed ($F_{3,21} = 4.38$, $p = 0.0152$). Least Squares Means post-hoc analysis identified that the PMFD for the long option (23.3 ±2.8 cm) was greater than for the short option (19.1 ±2.9 cm). Also, PMFD for the medial (20.9 ±0.9 cm) and lateral (20.8 ±0.7 cm) options were smaller than PMFD for the long option. For the ML obstacle, a main effect of option was also observed ($F_{3,21} = 222.97$, $p < 0.0001$). Post-hoc analysis showed a difference between all pairwise comparisons, except for the medial (12.4 ±0.9 cm) versus lateral (12.4 ±0.7 cm) options comparison. For the ML obstacle, the mean value for the PMFD for the long option was equal to 35.8 ±2.8 cm whereas for the short option it was equal to 31.6 ±2.9 cm.

*Is the foot placement modification vector magnitude different for dominant and non-dominant adjustments?*

The two-way ANOVA (Condition x Step) with repeated measures in both factors for the long and short forced conditions identified a main effect of condition ($F_{1,7} = 6.96$, $p = 0.0335$) and an interaction effect ($F_{1,14} = 37.27$, $p < 0.0001$). Least Squares Means post-hoc analysis for the interaction effect identified that the foot placement modification vector magnitude was the same in step N (long forced: 27.8 ±4.8 cm; short forced: 24.3 ±7.6 cm), but it was larger for the long forced adjustment (31.6 ±6.9 cm) than for the short forced adjustment (18.8 ±7.0 cm) in step N+1. For the analysis involving the long and short free adjustments, the condition effect just failed to achieve significance ($F_{1,6} = 5.37$, $p = 0.0596$). Foot placement modification vector magnitude for the long free adjustment (28.7 cm) tended to be greater than for the short free adjustment (20.8 cm). There was no difference between forced and free conditions for both long and short adjustments.

For the ANOVA including medial and lateral adjustments, main effects of step ($F_{1,21} = 6.26$, $p = 0.0207$) and condition ($F_{1,14} = 11.51$, $p = 0.0011$) as well as an interaction effect ($F_{2,21} = 23.15$, $p < 0.0001$) were found. Least Squares Means post-hoc analysis for the interaction effect identified that the foot placement modification vector magnitude was equal among conditions in step N (lateral forced: 15.7 ±5.1 cm; lateral free: 13.9 ±3.3 cm; medial forced: 14.1 ±6.8 cm), but it substantially increased in step N+1 for the medial forced adjustment (lateral forced: 14.1 ±3.6 cm; lateral free: 10.2 ±1.9 cm; medial forced: 28.0 ±11.1 cm). No difference was observed between lateral forced and free adjustments.

*Are the foot and COM vectors tightly coupled during the execution of the alternate foot placement?*

For the long (forced and free) and short free adjustments, there seems to exist a good coupling between foot and COM in both steps (N and N+1) (Figure 6). For the short forced adjustment, this is not the case in step N. In some of the trials, the foot moves backwards in order to achieve the goal of the task whereas the COM moves forward, creating a very unstable gait as illustrated in Figure 7, where COM projection on the ground is clearly ahead of the BOS. Results of the ANOVAs for the cosine of the absolute angle difference are shown in Table 2 and mean values are plotted in Figure 9. The interaction effect for the long forced and short forced analysis resulted from the increased angle difference for the short forced adjustment in step N (cosine = 0.37). No difference was observed between long forced and free adjustments. For the short forced adjustment, there was a substantial increase of the angle difference in comparison to short free adjustment in step N, but no difference was observed in step N+1.

Figure 8 shows the foot and COM vector distribution for the lateral and medial adjustments. For the lateral adjustment, the existence of decoupling between foot and COM in step N in both forced and free conditions is quite clear. A similar decoupling is also observed for the medial forced adjustment. For the medial free condition, this is not clear. The interaction effect shown in the Table 2 reveals no significant difference between lateral forced and medial forced adjustments in step N, but there was a significant difference in step N+1, where a tightening coupling was observed for the medial forced adjustment. There was no difference between lateral forced and free adjustments.

*Table 2*. Output of the ANOVAs for the cosine of the difference between foot placement modification vector orientation and COM modification vector orientation. Probability values in italics indicate the presence of main/interaction effects.

| Conditions | Effects | DF | F Value | Pr > F |
|---|---|---|---|---|
| | Condition | 1, 7 | 7.38 | *0.0299* |
| LonFo / ShoFo | Step * | 1, 14 | 7.17 | *0.0180* |
| | Interaction | 1, 14 | 7.12 | *0.0184* |
| | Condition | 1, 6 | 1.76 | 0.2326 |
| LonFr / ShoFr | Step | 1, 12 | 1.21 | 0.2922 |
| | Interaction | 1, 12 | 1.33 | 0.2710 |
| | Condition | 1, 7 | 0.85 | 0.3865 |
| LonFo / LonFr | Step | 1, 14 | 0.00 | 0.9924 |
| | Interaction | 1, 14 | 1.61 | 0.2250 |
| | Condition | 1, 6 | 5.93 | *0.0507* |
| ShoFo / ShoFr | Step | 1, 12 | 9.32 | *0.0100* |
| | Interaction | 1, 12 | 6.44 | *0.0261* |
| | Condition | 2, 14 | 0.39 | 0.6818 |
| LatFo / LatFr / MedFo | Step | 1, 21 | 14.30 | *0.0011* |
| | Interaction | 2, 21 | 8.67 | *0.0018* |

*N and N+1
LonFo = long forced; LonFr = long free; ShoFo = short forced; ShoFr = short free; LatFo = lateral forced; LatFr = lateral free; MedFo = medial forced; DF = degrees of freedom

*Is forward progression of body COM compromised during alternate foot placement?*

The only ANOVA that indicated a main effect of condition was the one including long forced and short forced adjustments ($F_{2,13} = 7.58$, $p = 0.0066$). The deviation for the long forced adjustment (1.6 ±1.1 degrees) is larger than for the short forced adjustment (0.3 ±1.3 degrees). For the ML obstacle, the one-way ANOVA with repeated measures showed a main effect of condition ($F_{3,21} = 39.05$, $p < 0.0001$). Post-hoc analysis indicated that there is no difference between lateral forced (-3.4 ±2.4 degrees) and free (-1.6 ±2.2 degrees) adjustments, but they are different from the medial forced adjustment (10.2 ±3.8 degrees). Lateral forced and medial forced were also different from WT (0.6 ±0.6 degrees). Lateral free and WT were not different from each other.

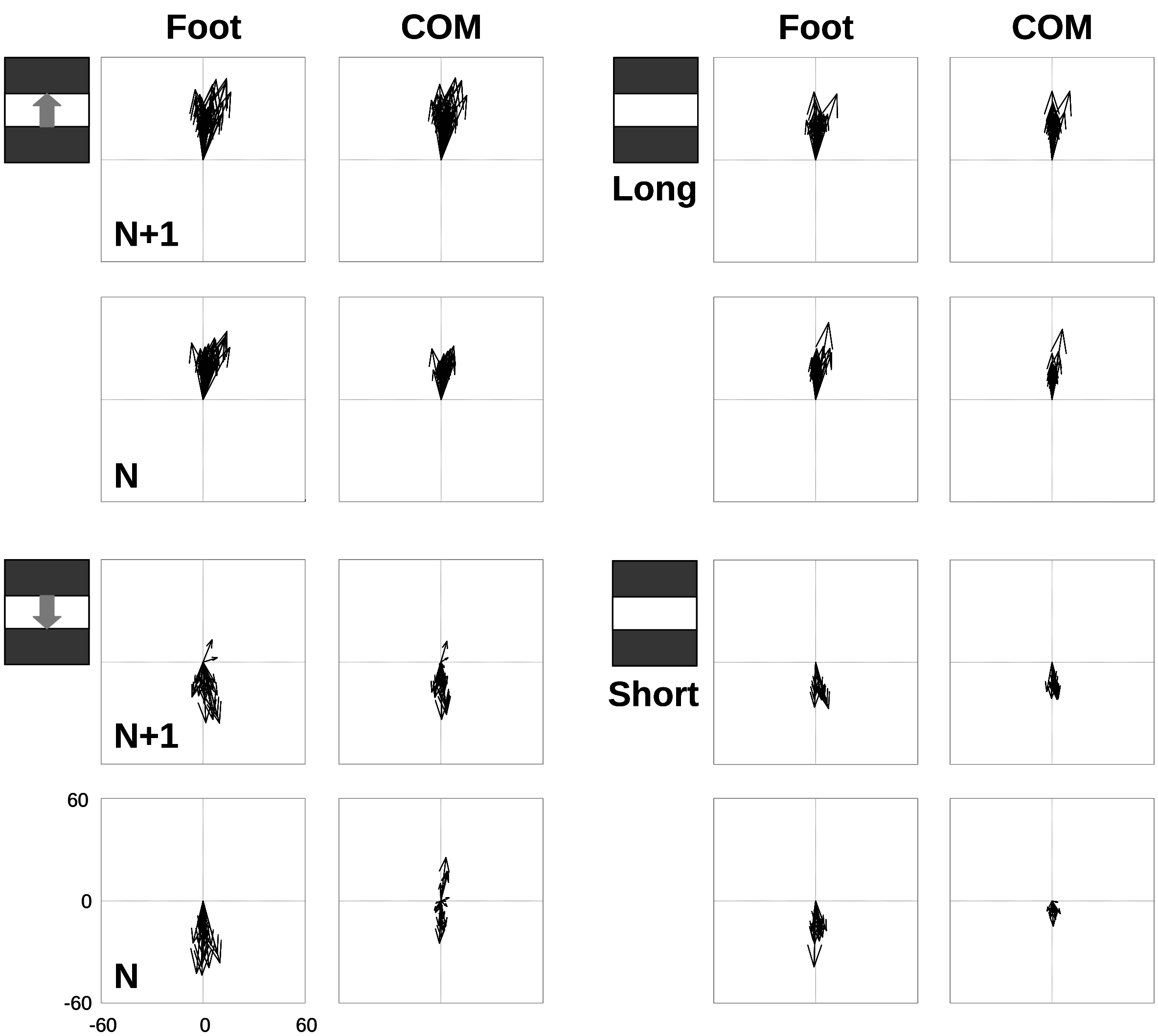


*Figure 6*. Foot and COM vector distribution plots (i.e., polar plots) of individual trials for steps N and N+1 for the long (top) and short (bottom) adjustments. Left side shows the forced condition and right side shows the free condition.

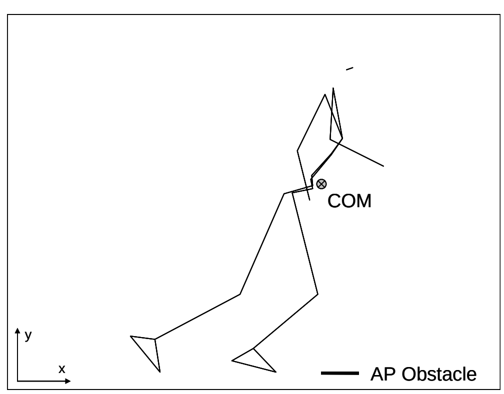


*Figure 7*. Stick figure in the sagittal plane of a participant performing a short forced adjustment.

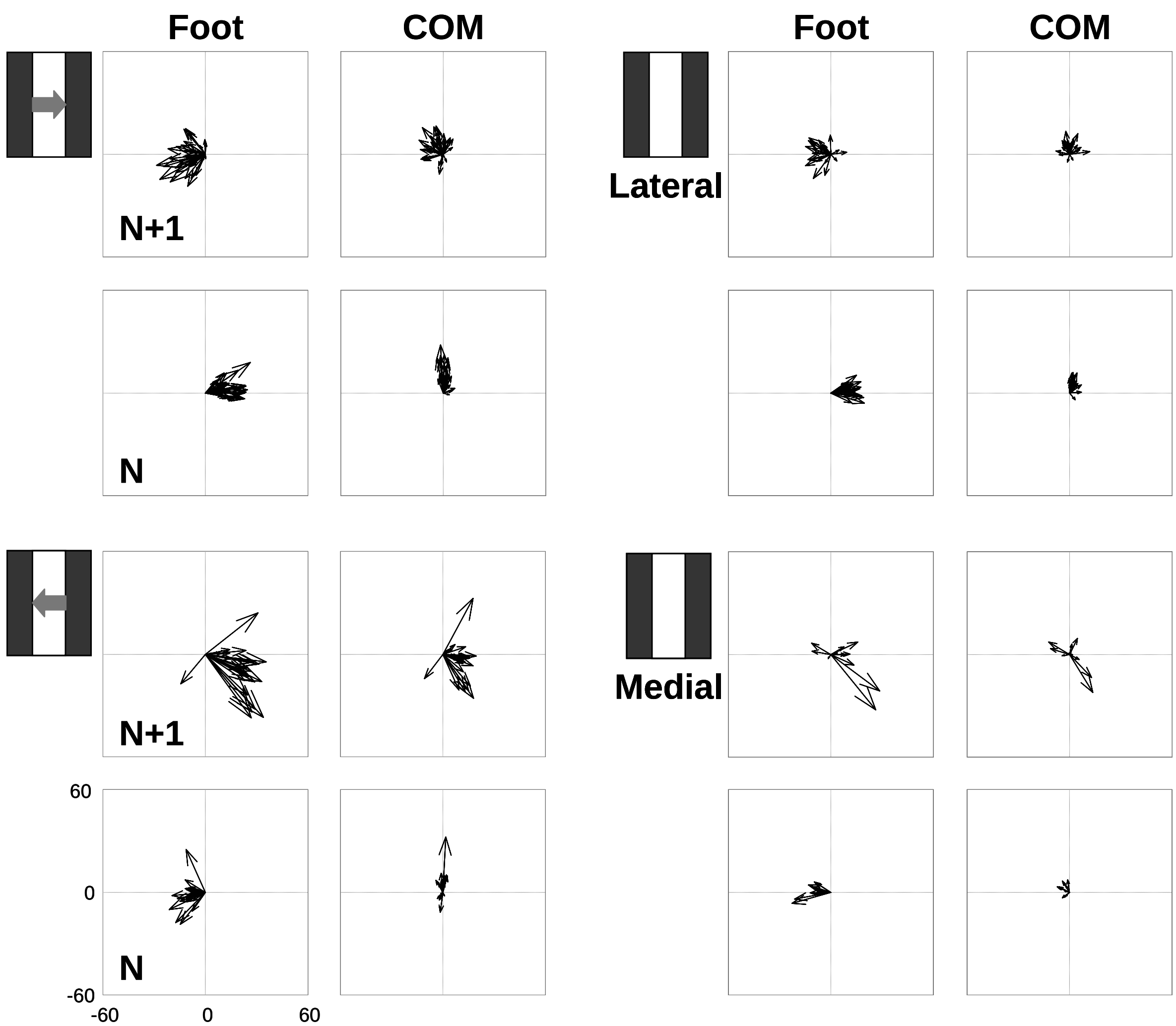


*Figure 8*. Foot and COM vector distribution plots (i.e., polar plots) of individual trials for steps N and N+1 for the lateral (top) and medial (bottom) adjustments. Left side shows the forced condition and right side shows the free condition.

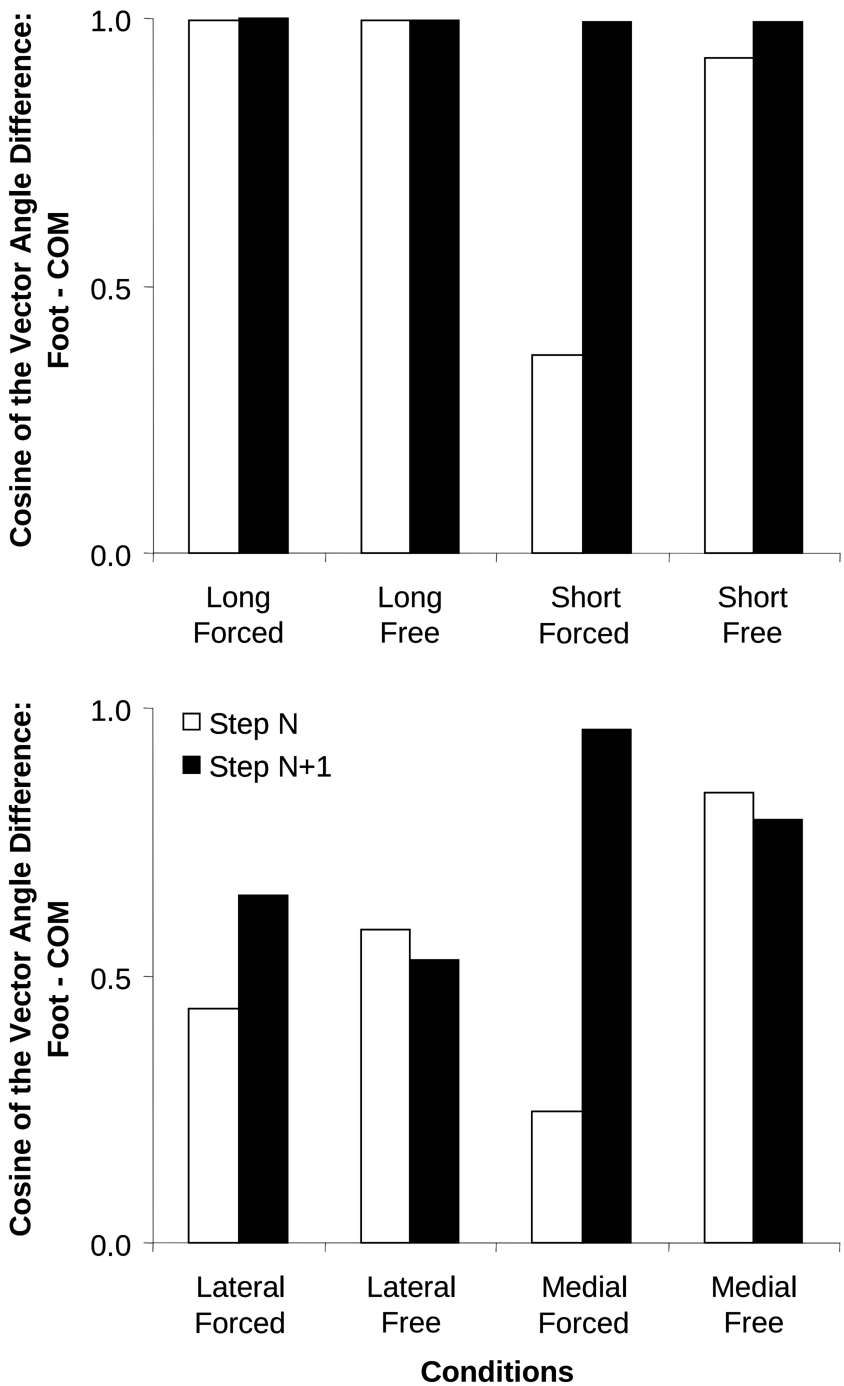


*Figure 9*. Mean cosine of the absolute difference between foot placement modification vector angle and COM modification vector angle in steps N (white bars) and N+1 (black bars).

*Are the dominant adjustments more stable than the non-dominant adjustments?*

Mean and standard deviations of the AP and ML distances of the COM relative to

BOS are plotted in Figure 10. Table 3 shows the results of the ANOVAs conducted for the AP and ML distances of the COM relative to BOS.

*Table 3*. Output of the ANOVAs for the stability variables. Probability values in italics indicate the presence of main/interaction effects.

| | | | COM-BOS AP Distance | | COM-BOS ML Distance | | Margin of Stability AP Distance | | Margin of Stability ML Distance | |
|---|---|---|---|---|---|---|---|---|---|---|
| Conditions | Effects | DF | F Value | Pr > F | F Value | Pr > F | F Value | Pr > F | F Value | Pr > F |
| LonFo | Condition | 2, 14 | 14.50 | *0.0004* | 3.90 | 0.0449 | 18.47 | <*.0001* | 0.03 | 0.9676 |
| ShoFo | Step * | 1, 21 | 0.15 | 0.7033 | 0.93 | 0.3468 | 12.21 | *0.0022* | 3.41 | 0.0788 |
| WT | Interaction | 2, 21 | 2.95 | 0.0745 | 1.82 | 0.1868 | 6.05 | *0.0084* | 1.32 | 0.2878 |
| LonFr | Condition | 2, 12 | 16.16 | *0.0004* | 1.74 | 0.2176 | 11.16 | *0.0018* | 0.44 | 0.6515 |
| ShoFr | Step | 1, 18 | 1.32 | 0.2653 | 0.39 | 0.5376 | 13.05 | *0.0020* | 1.73 | 0.2045 |
| WT | Interaction | 2, 18 | 8.81 | *0.0021* | 1.73 | 0.2059 | 1.08 | 0.3618 | 1.06 | 0.3685 |
| LonFo | Condition | 2, 14 | 50.84 | <*.0001* | 2.67 | 0.1041 | 10.00 | *0.0020* | 0.19 | 0.8325 |
| LonFr | Step | 1, 21 | 3.65 | 0.0700 | 0.15 | 0.7062 | 7.14 | *0.0143* | 14.25 | *0.0011* |
| WT | Interaction | 2, 21 | 6.47 | *0.0065* | 2.64 | 0.0951 | 0.72 | 0.4999 | 0.15 | 0.8652 |
| ShoFo | Condition | 2, 12 | 22.70 | <*.0001* | 0.82 | 0.4618 | 28.20 | <*.0001* | 0.34 | 0.7170 |
| ShoFr | Step | 1, 18 | 4.35 | 0.0515 | 0.97 | 0.3384 | 49.12 | <*.0001* | 0.39 | 0.5424 |
| WT | Interaction | 2, 18 | 2.07 | 0.1549 | 1.07 | 0.3624 | 14.91 | *0.0002* | 0.56 | 0.5782 |
| LatFo / LatFr MedFo / WT | Condition | 3, 21 | 67.19 | <*.0001* | 121.26 | <*.0001* | 8.75 | *0.0006* | 113.61 | <*.0001* |
| | Step | 1, 28 | 21.91 | <*.0001* | 11.98 | *0.0017* | 0.56 | 0.4606 | 218.81 | <*.0001* |
| | Interaction | 3, 28 | 24.27 | <*.0001* | 7.10 | *0.0011* | 1.19 | 0.3322 | 35.05 | <*.0001* |

* N and N+1.
LonFo = long forced; LonFr = long free; ShoFo = short forced; ShoFr = short free; LatFo = lateral forced; LatFr = lateral free; MedFo = medial forced; DF = degrees of freedom

*COM-BOS AP distance: long-short adjustments*. Post-hoc analysis for the main effect of condition showed that AP distance was larger for short forced adjustment (7.2 cm) than for long forced adjustment (4.5 cm) and WT (0.8 cm), which were also different from each other. Visual inspection of Figure 10 indicates that the AP distance is similar in steps N and N+1 for the short forced adjustment and it diminishes in step N+1 for the long forced adjustment. However, the interaction effect just failed to achieve significance (p = 0.07).

The post-hoc analysis for the interaction effect for the long and short free analysis indicated that AP distance was different among all conditions in step N. In step N+1, there was no difference between long free adjustment and WT, but the AP distance was larger for the short free adjustment than for the other two conditions. No difference was observed between long forced and free adjustments. The interaction effect for this analysis reflected the difference between them and WT in step N. For the short forced versus free analysis, AP distance was greater for the short forced adjustment than for the short free adjustment, which was larger than for the WT.

*COM-BOS AP distance: lateral-medial adjustments*. In step N, AP distance for the lateral forced adjustment was larger than for the lateral free adjustment, which was also larger than for the WT and medial forced adjustment. In addition, AP distance for the WT was larger than for the medial forced adjustment. In step N+1, there was no difference between lateral forced and free adjustments and WT, but AP distance was greater for the WT than for the medial forced adjustment. The negative values for the medial forced condition could be seen as a good result since negative values could indicate that COM was within BOS. However, that was not the case for the medial forced adjustment, because in 75% of the trials COM was behind the posterior margin of the BOS in both steps. On the other hand, for the medial free adjustment, in 88.9% of the trials, COM was inside BOS in step N and ahead of BOS for 66.7% of the trials in step N+1 (Figure 11).

*COM-BOS ML distance: long-short adjustments*. ML distance for the long forced adjustment was greater than for the short forced adjustment, but it was not different from WT. In general, the results for the ML distance for long and short adjustments pointed to the fact that adjustments for the AP obstacle were performed mainly in the plane of progression.

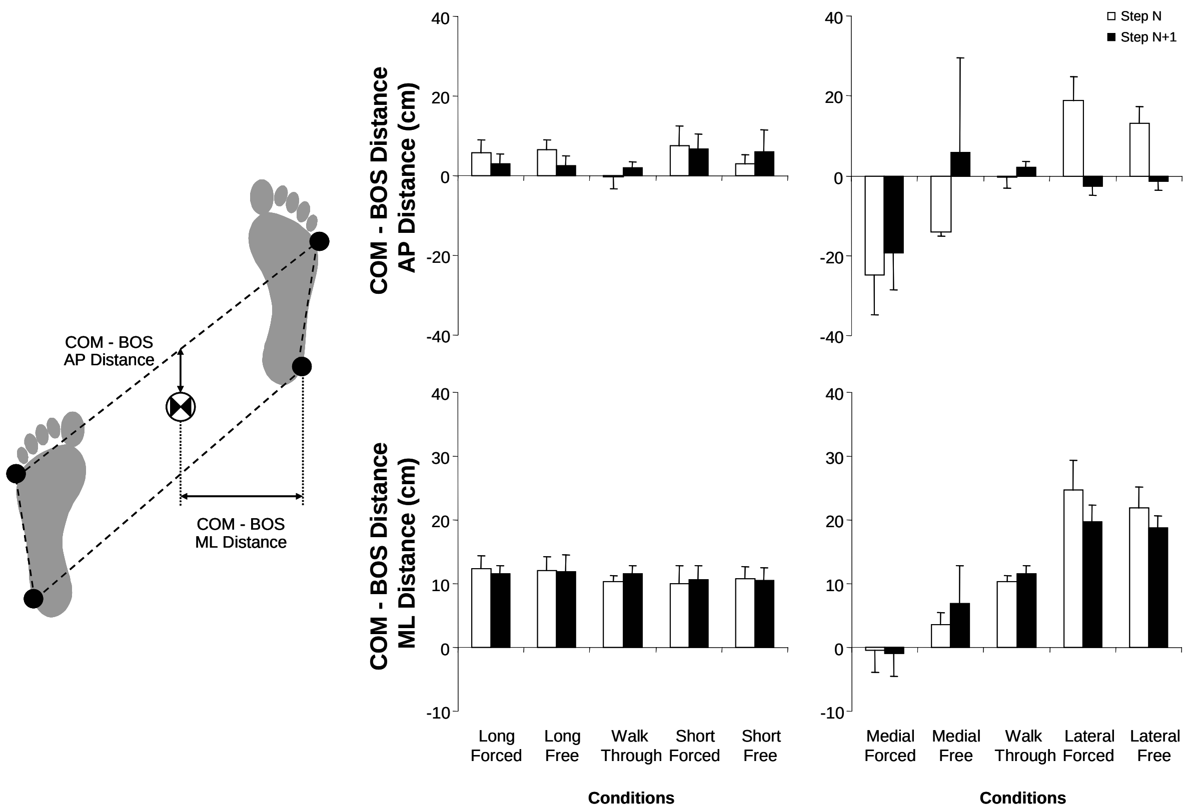


*Figure 10*. Anteroposterior (AP) and mediolateral (ML) distance of the COM in relation to anterior and lateral margins of the base of support, respectively. Left figure illustrates the measurements taken. Bar graphs show the mean and standard deviation for long-short adjustments (left column) and lateral-medial adjustments (right column) in both steps N (white bars) and N+1 (black bars). Top graphs show the AP distance and bottom graphs shows the ML distance.

*COM-BOS ML distance: lateral-medial adjustments*. ML distance for the lateral forced and free adjustments were greater than for the WT and medial forced adjustment in both steps. ML distance for the WT was also larger than for the medial forced adjustment. Furthermore, there was a difference between steps N and N+1 for lateral forced and free adjustments, but no difference was observed between steps for WT and medial forced adjustment. In fact, the medial forced adjustment was slightly challenging since, on average, COM was not within BOS as illustrated by Figure 11. No difference between lateral forced and free adjustments was observed.

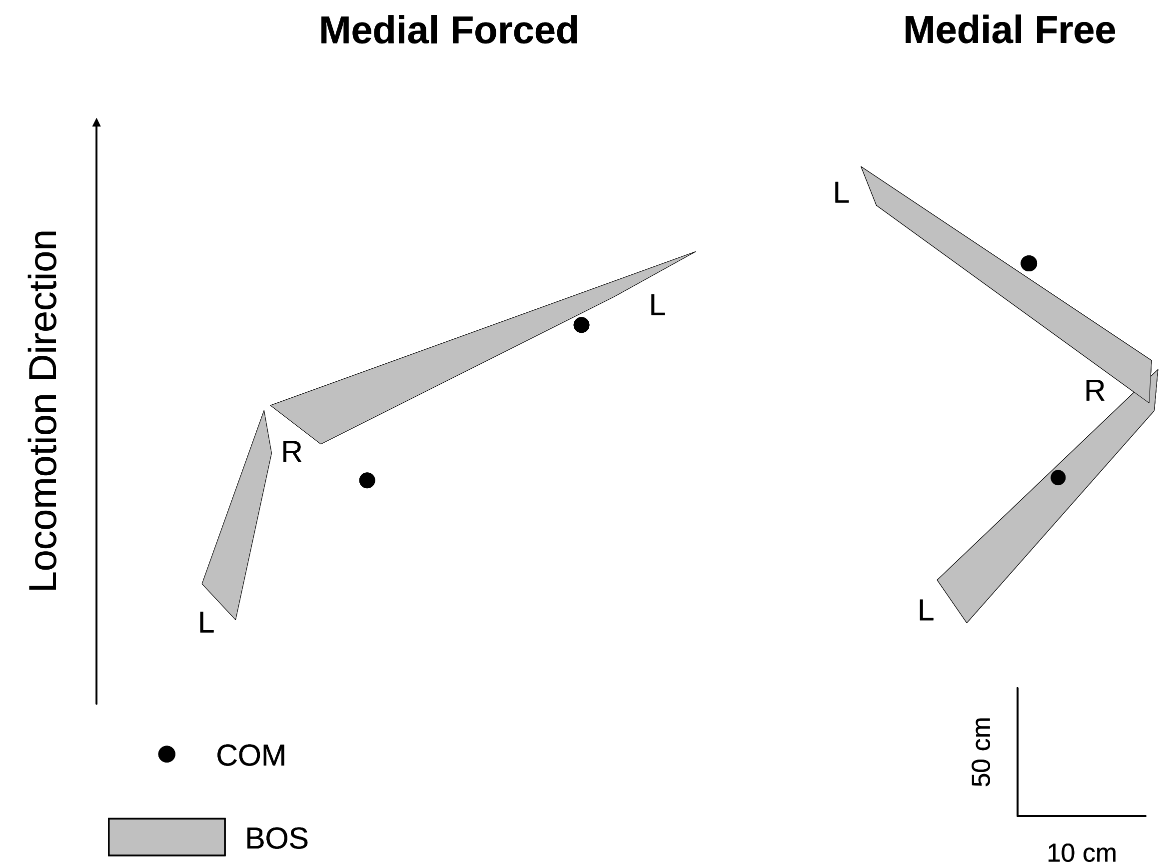


*Figure 11*. Transverse view of the COM location in relation to BOS as defined by foot markers for one trial in the medial forced (left side) and free (right side) conditions. (L = left foot; R = right foot)

*MDS: long-short adjustments*. Mean and standard deviations of the MDS are plotted in Figure 12. MDS in the AP direction was smaller for the short forced adjustment than for the long forced adjustment and WT in step N, which were not different from each other. In step N+1, no difference was found between long and short forced adjustments, but MDS was smaller for the short forced adjustment than for the WT. The condition effect for the long and short free adjustments analysis indicated that both adjustments reduced the MDS compared to WT. The difference between long and short free adjustments just failed to achieve statistical significance ($p = 0.0552$). The condition effect for the long forced and free analysis indicated that no difference was found between long forced and free adjustments, although both conditions exhibited a smaller MDS than WT. For the analysis involving short forced and free adjustments, the interaction effect indicated that both short forced and free adjustments presented a smaller MDS than WT in step N. In addition, MDS was smaller for the short forced adjustment than for the short free adjustment. In step N+1, no difference was observed between short forced and free adjustments, but both adjustments exhibited a smaller MDS compared to WT. In the ML direction, no difference for MDS was observed among conditions.

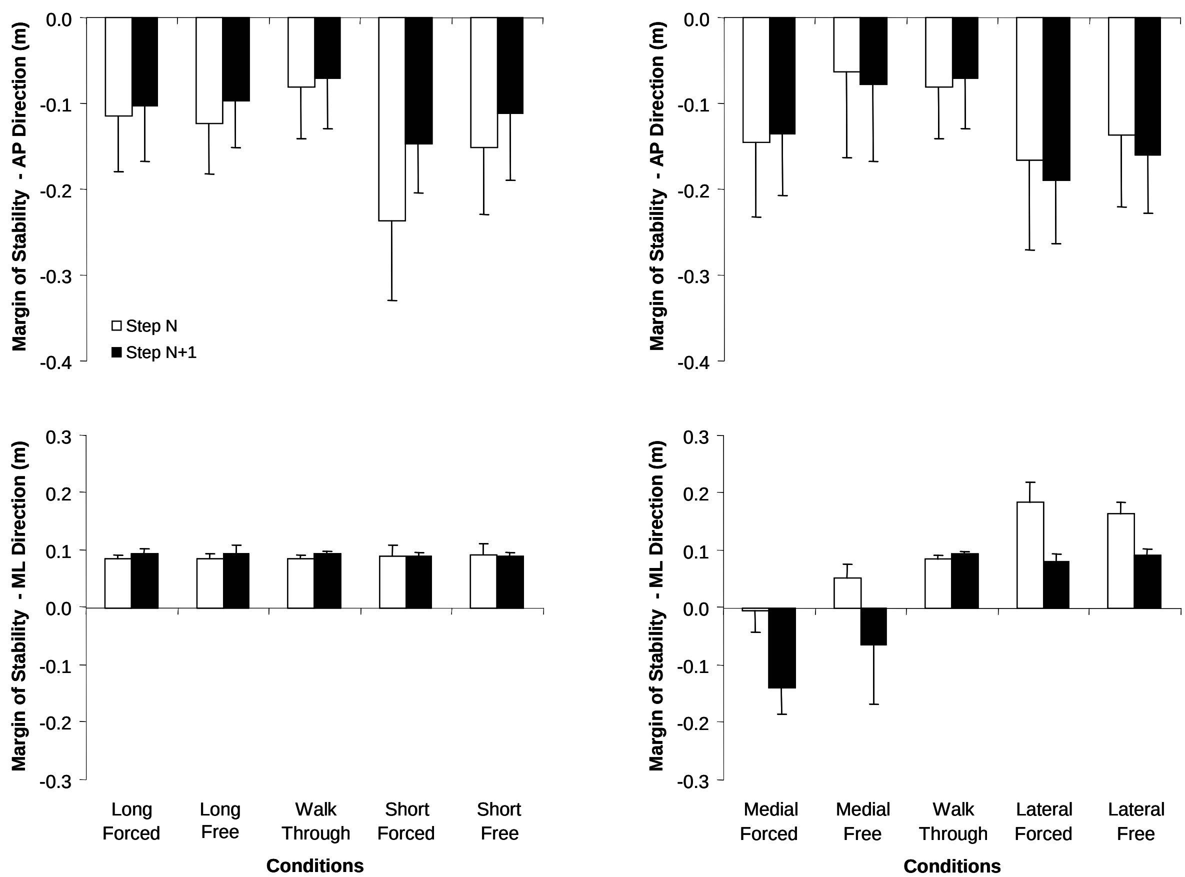


*Figure 12*. Mean and standard deviation for the margin of dynamic stability for the long/short (left column) and lateral/medial (right column) adjustments in both steps N (white bars) and N+1 (black bars). Data for the AP and ML directions are shown respectively in the top and bottom rows.

*MDS: lateral-medial adjustments*. In the AP direction, the condition effect indicated that all three adjustments (lateral forced and free and medial forced) exhibited a smaller MDS than WT. In the ML direction, the interaction effect indicated that MDS was larger for the lateral adjustments (forced and free) than for the WT and medial forced adjustment in step N. In addition, WT exhibited a larger MDS than medial forced adjustment in the same step. In step N+1, no difference was observed between lateral adjustments (forced and free) and WT, but the medial forced adjustment exhibited a smaller MDS than all other three conditions. No difference was found between lateral forced and free adjustments.

*Are the step parameters modulated according to the alternate foot placement adjustments?* The statistical analyses results for the step parameters are shown in Table 4. Mean and standard deviation data for SL and SW are plotted in Figure 13. As expected, SL increased for the long adjustments (forced and free) and decreased for the short adjustments (forced and free) in relation to WT. In step N+1, SL was not different among the conditions, except for the short forced adjustment, where it increased. In general, SW was not affected by the conditions for the AP obstacle. The only exception was observed for the long forced adjustment in step N, where it increased in comparison to WT and short forced adjustments. For the adjustments in the ML direction, SL was reduced in step N+1 compared to step N. As expected, SW increased for the lateral adjustments (forced and free) and decreased for the medial forced adjustment in comparison to WT in step N. Interestingly, it increased even more in step N+1 for the lateral adjustments. For the medial adjustment, it was negative in step N+1, indicating that participants crossed their steps.

*Table 4*. Output of the ANOVAs for the step length and width variables. Probability values in italics indicate the presence of main/interaction effects.

| | | | Step Length | | Step Width | |
|---|---|---|---|---|---|---|
| Conditions | Effects | DF | F Value | Pr > F | F Value | Pr > F |
| | Condition | 2, 14 | 132.25 | *<.0001* | 3.91 | *0.0446* |
| LonFo / ShoFo / WT | Step * | 1, 21 | 0.44 | 0.5121 | 0.24 | 0.6320 |
| | Interaction | 2, 21 | 117.29 | *<.0001* | 5.02 | *0.0166* |
| | Condition | 2, 12 | 209.61 | *<.0001* | 1.78 | 0.2099 |
| LonFr / ShoFr / WT | Step | 1, 18 | 1.81 | 0.1947 | 0.03 | 0.8642 |
| | Interaction | 2, 18 | 40.43 | *<.0001* | 0.85 | 0.4440 |
| | Condition | 2, 14 | 201.99 | *<.0001* | 2.87 | 0.0905 |
| LonFo / LonFr / WT | Step | 1, 21 | 123.21 | *<.0001* | 2.22 | 0.1515 |
| | Interaction | 2, 21 | 23.70 | *<.0001* | 2.76 | 0.0865 |
| | Condition | 2, 12 | 30.11 | *<.0001* | 0.41 | 0.6714 |
| ShoFo / ShoFr / WT | Step | 1, 18 | 93.03 | *<.0001* | 0.27 | 0.6067 |
| | Interaction | 2, 18 | 32.84 | *<.0001* | 0.42 | 0.6614 |
| | Condition | 3, 21 | 0.98 | 0.4197 | 103.41 | *<.0001* |
| LatFo / LatFr / MedFo / WT | Step | 1, 28 | 8.73 | *0.0063* | 0.08 | 0.7758 |
| | Interaction | 2, 21 | 0.35 | 0.7865 | 57.67 | *<.0001* |

* N and N+1.
LonFo = long forced; LonFr = long free; ShoFo = short forced; ShoFr = short free; LatFo = lateral forced; LatFr = lateral free; MedFo = medial forced; DF = degrees of freedom

## Discussion

This study was designed to validate the stability and maintenance of forward progression determinants when planning the alternate foot placement using the selection algorithm proposed by Patla et al. (1999) and expanded by Moraes et al. (2004). When participants decided where to place their foot to avoid an obstacle (free condition), allowed us to investigate the preferred choice in each plane of movement (i.e., frontal and sagittal) when the amount of foot displacement for the alternate foot placement was similar for lengthening or shortening the step in the plane of progression, and for widening or narrowing the step in the frontal plane. The forced condition removed the planning component of the alternate foot placement and filled the gaps for the non-dominant choice. In the forced condition, a green arrow was displayed on the top of the obstacle, indicating the direction of alternate foot placement. An arrow as a cue is a common signal for indicating directions present in our environment. In fact, Kingstone et al. (2003) noted that arrows are a good cue for shifting attention and helping reduce reaction time. Therefore, the arrow was an appropriate trigger to cue the location of alternate foot placement.

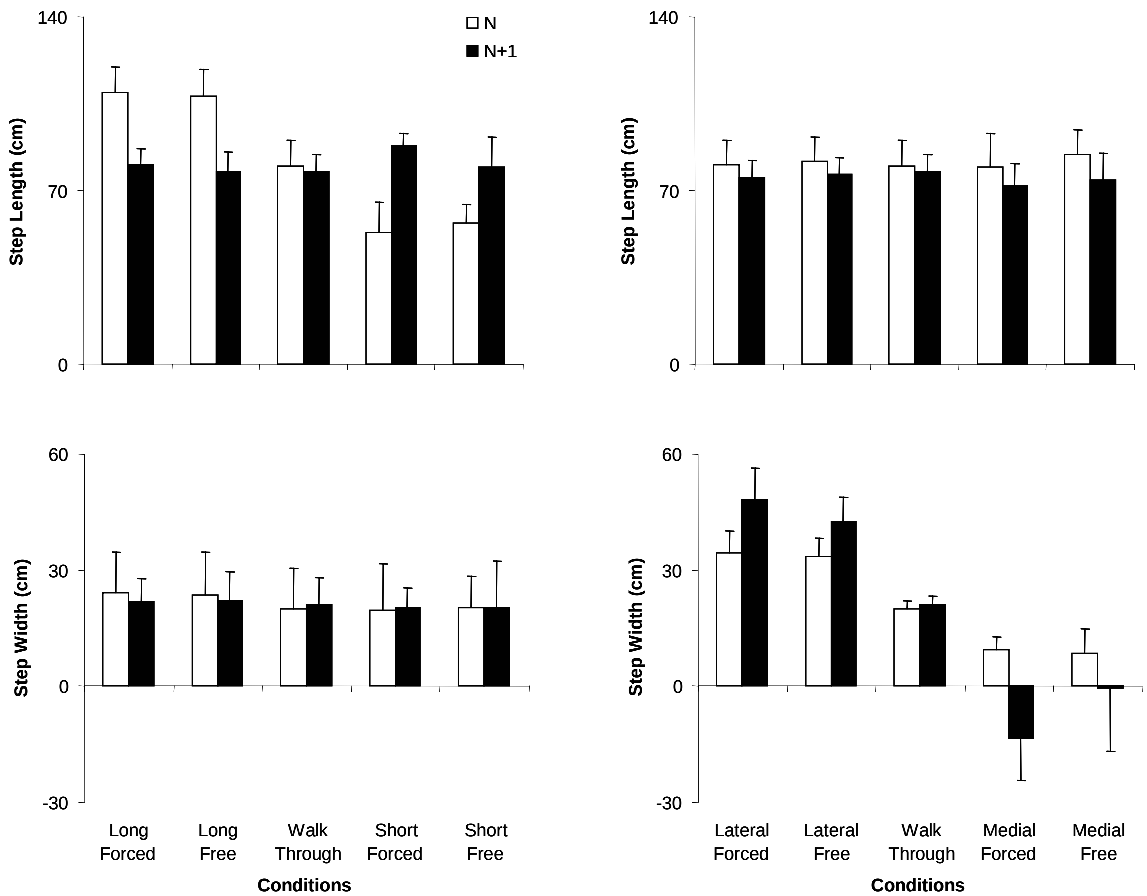


*Figure 13*. Mean and standard deviation for the step length (top row) and step width (bottom row) for the long/short (left column) and lateral/medial (right column) adjustments in both steps N (white bars) and N+1 (black bars).

### *Movement planning time does not bias the preferred alternate foot placement*

Onset of deviation in limb trajectory was used as an estimate of the time required for movement planning and initiation of a change. The information processing requirements for planning the alternate foot placement for changes within the sagittal plane or frontal plane are the same and are not reasons for biasing the preferred choice in each plane of movement. In addition, onset time of limb trajectory change was unaffected by condition (forced and free). The only exception was observed for the short free adjustment, which exhibited an earlier onset (~ 40 ms). The early onset exhibited by short free adjustment may be a consequence of the need to appropriately reduce forward momentum rather than having less time to plan alternate foot placement. One of the great challenges of shortening the step is the proper control of linear forward momentum in order to avoid creating a large angular momentum (Patla et al. 1999). It is possible that short free adjustments began earlier in order to guarantee more time for the proper control of linear forward momentum. As is shown in Figure 7, short forced adjustments produced an unstable posture. Patla et al. (1989a) has shown that the success rate for shortening the step decreases substantially when the cue is provided 100 ms after contralateral HC. The same reduction does not occur when the cue for lengthening the step takes place 100 ms later. Therefore, time seems to be a critical parameter when shortening the step length within one step cycle.

Onset time of limb trajectory change was, on average, shorter for changes in the ML direction (290 ms) than for changes in the AP direction (370 ms). This time includes gathering appropriate sensory information (about obstacle size/orientation; location of the foot if no changes are made), running the putative algorithm to arrive at a selection, and initiating the change at appropriate time. For instance, the required processing time for the long adjustment may be shorter than 370 ms, but there may be an optimum time for its implementation. Drew et al. (2004) argued that changes in gait used to avoid obstacles need to be integrated appropriately with the underlying pattern of activity in order to guarantee smooth adaptations. Because there may be a need for a more substantial change, implementation of the alternate foot placement in the ML direction would be “stronger” than in the AP direction and therefore the ankle velocity profile in the ML direction would change earlier than in the AP direction. Patla et al. (1999) found that when the same amount of foot displacement exists in both the sagittal and frontal planes, changes in the sagittal plane are preferred because they can be implemented through the modulation of ongoing muscle activity. Alternate foot placement in ML direction would result in more substantial changes than in AP direction.

*Initial slowing response to all adjustments provides more time for planning and decision-making*

For all changes in foot placement (i.e., long, short, lateral, and medial) there was an increase in braking impulse in the AP and vertical directions. The consistency of this change across different conditions suggests that such changes may not be directly related to step change implementation, but rather to the gathering of more time for planning alternate foot placement. The data available in the literature (Patla 1991; Patla et al. 1989a, 1991) show that there is no increase in braking impulse in either AP or vertical directions for lengthening the step; no increase in the vertical direction for widening the step; and no increase in the AP direction for shortening the step. The studies described in the literature used a visual cue to indicate what change to implement (i.e., lengthening, shortening, or widening). Hence, decision-making was simple, since each light cue was coupled to a specific step parameter modulation. In the present study, participants had to decide what modification to make in order to avoid the obstacle; hence, the decision-making process is more complex and would demand more time for processing. It is not the case that participants were startled with the sudden obstacle appearance and slowed their movements down. Patla et al. (1989a) have shown that braking impulse responses are specific for shortening and lengthening the step when using a light cue. Thus, the increased braking impulse in the AP and vertical directions could be seen as a strategy for slowing down body movement in order to get extra time for planning alternate foot placement.

However, the amount of change is not consistent across conditions. For instance, in the vertical direction the mean increase in braking impulse was equal to 8.4%, 27.3%, 15.1%, and 19.4% for the long, short, lateral, and medial adjustments, respectively. For the short condition, it is clearly higher than for the other conditions, which may also suggest that part of the changes in braking impulse in the AP and vertical directions are directly related to the alternate foot placement implementation. In addition, the increase in braking impulse in the ML direction for the lateral adjustment was equal to 57%. Increasing the braking impulse in the ML direction helps reduce the COM displacement on the contralateral side; consequently, it facilitates moving COM to the ipsilateral side and the lateral adjustment. Furthermore, onset of limb trajectory change occurred earlier than the end of the braking period for the short, lateral, and medial adjustments (110 ms on average), whereas for the long adjustment it occurred at the same time as the end of the braking period (-8 ms on average). Therefore, the changes in the braking impulse are likely related to both explanations: 1) to get more time for decision-making, and 2) to implement effective changes related to the alternate foot placement.

Lengthening the step was accomplished by increasing the propulsive impulse in the AP and vertical directions and vice-versa for shortening it. The increase in the AP impulse helped in moving the body forward, whereas the increase in the vertical impulse helped in increasing the step duration. The opposite was true for shortening the step (Patla et al. 1989a). For narrowing and widening the step, the major changes are observed in the ML propulsive impulse. For the lateral adjustment, there is an increase of 97.8% in the ML propulsive impulse, whereas for the medial adjustment there is a decrease of 143.3% in the ML propulsive impulse. The increase in propulsive impulse for the lateral adjustment helped move the body laterally (Patla et al. 1991). For the medial direction, the reduction and change in polarity of the propulsive impulse reduces the lateral movement of the body and moves the body medially.

*Amount of foot displacement from its normal landing position is not the sole predictor of the preferred alternate foot placement choice*

Although the PMFD was greater for the long adjustment than for the short adjustment, the dominant response was long in the free condition. Patla et al. (1999) suggested that when there is only one option that minimizes foot displacement, it is the preferred choice. Moraes et al. (2004) proposed that minimum foot displacement is not the major determinant guiding the selection of alternate foot placement. They suggested that when more steps are available for planning and implementing the alternate foot placement, maintenance of forward progression seems to be more important than minimizing foot displacement. The present finding suggests the existence of a threshold, where the switch to short adjustments occurs only when long adjustments represent a substantial increase in step length that may be uneconomical and/or unstable. A recent study by Greig et al. (2004) suggested that the switch from long to short occurs when the amount of foot displacement for the long adjustment exceeds the short one by more than 7 cm. As the difference in the present study is approximately 4 cm, the long preference is not surprising.

Foot placement modification vector magnitude was approximately 4.0 cm greater for long adjustments as compared to short adjustments. No difference was observed between medial and lateral adjustments. In addition, the difference between PMFD and foot placement modification vector magnitude was approximately 4.0 cm for the long and short adjustments and 2.0 cm for the medial and lateral adjustments. In all adjustments, participants tried to minimize foot displacement. Therefore, since the difference between PMFD and foot placement modification vector magnitude is the same for long/short and lateral/medial adjustments, and long adjustment is preferred even though it results in a greater displacement of the foot, the amount of foot displacement from its normal landing position is not sole the predictor of the preferred alternate foot placement choice.

*Long and lateral adjustments are dominant and more natural to implement than short and medial adjustments*

As expected, long adjustment was preferred over short adjustment in the free condition, even though long adjustment had a greater predicted minimum foot displacement than short adjustment. In addition, lateral adjustment was preferred over medial adjustment, which contradicts the medial preference reported by Patla et al. (1999). Predicted minimum foot displacement does not bias the lateral choice since there is no difference between PMFD for medial and lateral adjustments. This lateral preference is in accordance with the results from Reynolds and Day (2005), who studied the visual control of foot trajectory from a standing position. In their study, participants were instructed to land the foot on a target that could change sideways at foot-off. They found that participants were able to make appropriate directional changes, although the magnitude of such changes dramatically reduced for the medial (7.4 cm) compared to the lateral (16.9 cm) target location.

The reason(s) for this inconsistency between the present study and Patla et al.'s study is not yet clear, but some methodological differences can be considered. Patla et al. (1999) used a mechanical apparatus with a piece of black cardboard with cuts and lights underneath it, indicating the planar obstacle. With such an apparatus, participants could get visual cues before the obstacle light was turned on, even though the room light was dim. Therefore, they could have used such visual cues to plan and implement the alternate foot placement in advance. This contrasts with the current experiment, where participants had no clue in advance because of the use of the LCD monitor. Moraes et al. (2004) found a medial preference when participants had 3 steps to plan and implement the alternate foot placement and they could see it from the beginning of the trial. Another issue may be related to stimulus identification (i.e., planar obstacle identification). Schmidt and Lee (2005) have suggested that stimulus intensity, i.e., the brightness of a light stimulus, has an effect on reaction time. In the original work, a mechanical apparatus with lights underneath was used and it created a brighter stimulus than the use of a LCD monitor. Further research is needed to identify the reasons for the bias in the frontal plane towards medial or lateral.

Success rate for the forced condition was much higher for long and lateral adjustments, which were the dominant choices in the free condition. For the short and medial adjustments, the success rate is low; the adjustments were in the wrong direction. In addition, the major wrong adjustments for the short and medial forced conditions are long and lateral adjustments, respectively. Therefore, it seems that long and lateral adjustments are more natural to implement than short and medial adjustments. During normal walking, COM moves forward and laterally along the medial border of the foot, creating a sinusoidal pattern (Winter 1991). As a consequence, long and lateral adjustments result in a more natural expansion of the COM trajectory since at HC the COM is moving forward and towards the new support limb.

*Maintenance of forward progression is consistent even for foot placement changes in the frontal plane*

For all adjustments, deviation from forward progression was minimal, except for the medial forced adjustment. In the plane of progression, there was no deviation from the goal although there is a difference between long and short forced. In addition, Figure 6 shows that COM vectors always lie in the plane of progression. In the frontal plane, as illustrated in Figure 8, COM continues to move forward, whereas the foot moves sideways in step N. This is illustrated by the decoupling between foot placement modification vector orientation and COM modification vector orientation (Figure 9). For the medial forced condition, the high degree of forward progression deviation was related to the unbalance in step N+1. Medial free adjustment resulted in a similar deviation, but in the opposite direction, as observed for the lateral adjustment. Thus, maintenance of forward progression is one of the major determinants guiding the selection of alternate foot placement.

*Stability guides the alternate foot placement choice under time pressure and similar minimum foot displacement*

Stability while performing the alternate foot placement was assessed by the AP and ML distance of the COM projection on the ground and the BOS defined by feet markers (Figure 10). Stability was also assessed by the MDS (Figure 12). The inclusion of the COM velocity in the stability analysis did show the same trend observed by the COM-BOS distance analysis, with the addition that the findings were more definitive for the MDS analysis than for the COM-BOS distance analysis. This is not completely surprising because human locomotion is characterized as a dynamic stable system. Even cockroaches with its tripod support ensuring static stability seem to exploit the advantages of dynamic stability when running at high speeds (Ting et al. 1994). However, it is important to mention that the values of the MDS are slightly higher because we estimated center of pressure from heel and fifth metatarsal markers. In their original work, Hof et al. (2005) measured directly the limits of center of pressure excursion and used that as the limit of the BOS.

The results of these two analyses clearly show that long adjustments are more stable than short adjustments, not only in step N, but also in step N+1, where there is no difference between long adjustments and normal walking. In addition, the fact that short adjustments do not return to baseline values in step N+1 suggests that they are not preferred, because it takes more time to recover from the changes in the locomotor behavior. Therefore, the central nervous system has the ability of predicting the consequences of shortening or lengthening the step to body stability and uses that information not only to choose what to do, but also to anticipate the disturbances, as proposed by Patla (2003).

It was proposed that long adjustment is preferred over short adjustment because the latter could lead to a substantial increase in angular momentum if not properly controlled (Patla et al. 1999; Moraes et al. 2004). The results for the short forced adjustment clearly exemplify this case (Figure 7). The reduced coupling between foot and COM vectors is an indication of such instability. In this case, COM continued to move forward while the foot moved backwards and stopped at HC. This creates a tendency for the body to fall forwards due to an increase in angular momentum. Therefore, shortening the step is not preferred because it takes longer to return to baseline value and, under time pressure, may lead to a substantial increase in angular momentum, which may result in a fall if recovery is unsuccessful.

In the ML direction, lateral adjustments are more stable than medial adjustments and this is shown by the COM-BOS ML distance, by MDS, and by the cross-over in step N+1 (illustrated by the negative step width (Figure 13)). Although the COM is within the BOS for the medial free adjustment in step N, it exhibited a very high percentage of cross-over (45.5%) in step N+1. For the medial forced adjustment, the cross-over percentage was even higher (88%). Lateral adjustment is not only stable in step N, but also in step N+1, where it shows the same COM-BOS AP distance and MDS in the ML direction as normal walking. For the COM-BOS ML distance, it was still greater than for normal walking, but this, in fact, increases stability. Although the increased distance of the foot relative to the COM may increase the destabilizing moment of force at the hip joint due to the large upper body mass (MacKinnon and Winter 1993), appropriate anticipatory control is needed to prevent this (Patla 2003). Therefore, the central nervous system again uses its predictive capacity to determine the more stable adjustment in the ML direction.

Moraes et al. (2004) suggested that medial adjustment was preferred because it would minimize COM acceleration in the frontal plane. This is not a wrong assumption (acceleration data are not shown, but the COM acceleration was reduced in the frontal plane for the medial adjustments), but the major problem with the medial adjustment is present in the step following the adaptive one. In particular, the cross-over is a great threat to the balance control system because it forces the swing limb to be moved sideways to avoid colliding with the support limb in the sequence of the gait cycle. In addition, in Moraes et al.'s study (2004), participants could implement the changes within three steps. Thus, they could properly accommodate the necessary adjustments and avoid the cross-over in the step following the obstacle.

It is also clear from the data for all the different adjustments that balance is more compromised in the adaptive step. This is not completely surprising since there are substantial changes in the gait behavior to accommodate the necessary alterations in foot placement. But, it is also interesting to note that the choices which are preferred resulted in a quicker return to baseline values in step N+1. Therefore, the central nervous system plans for the choice that minimizes threats to stability in step N and also guarantees a faster return of the stability parameters to baseline values in subsequent steps (normal walking).

Foot displacement from its normal landing position and maintenance of forward progression were not affected by the alternate foot placement choices. Stability was the only determinant that seemed to be more affected by the alternate foot placement choices. Long and lateral preferences exhibited a more stable behavior than short and medial adjustments, respectively. Therefore, under time pressure and similar displacement of the foot from its normal landing position, stability is the major determinant driving the selection of the alternate foot placement.

*Externally triggered adjustments amplify potential threats to body stability*

The results for the stability variables during the alternate foot placement in the forced condition showed that there was an increase of the AP distance between COM and BOS compared to the free condition, except for the long adjustment. This increase in the AP distance points to the fact that in the forced condition, COM moved more forward, which is a clear indication of decreased stability. Although there is no statistical analysis involving medial forced and free adjustments, visual inspection of the Figure 10 indicates that medial forced adjustment resulted also in a less stable behavior. In both AP and ML directions, COM was outside of the BOS. The MDS analysis also showed a difference between forced and free conditions, but only for the short adjustment.

The use of an arrow to trigger the alternate foot placement location changed the nature of the task. In the condition with the arrow, alternate foot placement was externally triggered, since the arrow's head indicated where to land. This condition is similar to experiments requiring participants to modulate step length/width or change in direction with a light cue (Patla et al. 1989a, 1991) during locomotion. In the free condition, the decision was internally generated, since participants decided where to land. Studies involving anticipatory postural adjustment when raising the arm while standing have shown a decrease in stability for externally triggered movements (Massion 1992; Nougier et al. 1999; Slijper et al. 2002). Nougier et al. (1999) requested participants to perform arm raising under two conditions. In one condition, participants self-initiated the arm movement within a 4 s period. In the other condition, participants raised the arm in reaction to a visual signal, which varied within a 4 s period. In the self-initiated condition, the range of the center of pressure excursion was smaller and center of pressure was located for a longer period of time around the average center of pressure. Furthermore, anticipatory postural adjustment was longer for the self-initiated condition and this was attributed to increased stability. Therefore, there is a less refined control of stability for externally triggered movements, which results in decreased stability.

We propose that modulation of the postural response is different between internally generated and externally triggered alternate foot placement. Neurophysiological studies have identified that different regions in the brain are involved with the planning and production of internally generated and externally triggered movements (Deiber et al. 1991; Cunnington et al. 1996; Jenkins et al. 2000; Obhi and Haggard 2004). Jenkins et al. (2000)

used regional cerebral blood flow to map the brain areas involved with extension movement of the index finger under a self-initiated condition and reaction time condition. They found a more extensive involvement of different brain areas for the self-initiated index finger extension than for the cued condition. Obhi and Haggard (2004) found that when performing a right index finger press, muscle activity diminished during the externally triggered movement. They suggested that this reduction in muscle activity resulted from decreased activation in the structures responsible for planning and producing the movement in the externally triggered condition. Others have suggested that hierarchically higher regions of the nervous system controlling the movement play a role in regulating the activity of subcortical networks related to the control of posture and movement (Prentice and Drew 2001; Drew et al. 2004; Schepens and Drew 2004; Massion 1992). Prentice and Drew (2001) showed that the activity of several neurons in the pontomedullary reticular formation exhibited multiple periods of increased activity. They suggested that these cells signal the timing and magnitude of the postural responses, rather than specifying a postural response. Therefore, if overall brain activity is reduced during externally triggered alternate foot placement, it is possible that the regulation of the pontomedullary reticular formation is also reduced, which in turn would affect the modulation of the postural response, leading to a less stable behaviour as observed in the forced condition for the short, lateral, and medial alternate foot placements.

*Summary*

In general, this study showed that long and lateral adjustments are preferred because they result in a more stable adaptation not only in the adaptive step, but also in subsequent step. Either medial or short adjustments require at least two steps to return the dynamic balance parameters to baseline values. Additionally, the different alternate foot placement choices do not compromise the maintenance of forward progression.

# Chapter 4

## Are alternate foot placement selections for avoiding two sequential planar obstacles planned individually or globally?

## Introduction

Previous studies involving alternate foot placement have used only one planar obstacle in the travel path (Patla et al. 1999; Moraes et al. 2004). These studies suggest that alternate foot placement is not solely sensory-driven and that three determinants are crucial for alternate foot placement selection: minimum foot displacement, stability, and maintenance of forward progression. Visual information is used to identify the undesirable landing spot, but it is not enough for selecting an alternate foot placement. The selected alternate foot placement incorporates all of these three determinants, weighting them properly according to obstacle location and size (Bahrami and Patla 2005). Although there seems to be a reasonable understanding of the alternate foot placement determinants for the avoidance of one obstacle, their applicability in more complex terrains is largely unknown. Thus, this is the first focus of the present study. The generality of these three determinants will be evaluated by placing two obstacles in sequence on a walkway. The inclusion of a second planar obstacle in the travel path will allow us to identify whether or not the same determinants are used or if additional ones are necessary for the second obstacle.

In addition to exploring if the same determinants are used when two obstacles are placed in sequence, the present study also addresses the issue of how alternate foot placements on complex terrain are planned. Fajen and Warren (2003) have suggested that during the avoidance of an obstacle in the travel path while walking towards a goal, route selection emerges from online steering dynamics, independent of explicit path planning. This kind of mechanism suggests that obstacles are avoided on an obstacle-by-obstacle basis according to when they are encountered in the travel path. However, Patla et al. (2004) have suggested that when travelling over complex terrain, individuals seem to plan routes that essentially avoid the crowded areas and, therefore, control is not obstacle-by-obstacle based (or online), but rather it is planned globally. In order to identify whether alternate foot placements are planned globally or online, the size of the second obstacle was manipulated. By looking at changes in alternate foot placement in the first obstacle due to changes in size in the second one, we can suggest how the movement was planned.

Although alternate foot placement selection is not solely sensory-driven, visual information is essential for two reasons. First, vision is the only sensory system that can provide accurate distant environmental information about both animate and inanimate objects (Patla 1997; Patla and Vickers 1997, 2003). This is critical in order to identify undesirable areas in the pathway in advance and properly plan the avoidance strategy. Second, visual information about obstacle location and self-motion combined with proprioceptive information about step length and width is used by the central nervous system (CNS) to estimate the normal landing position of the foot as well as the necessary amount of foot displacement required to avoid the obstacle (Patla et al. 1999; Moraes et al. 2004). The nature of visual information can be studied by identifying gaze fixation. Fixation in a specific location brings the fovea directly to that spot, which enhances visual resolution (Findlay and Gilchrist 2003). Previous studies have shown that gaze fixations are not random, but rather that individuals fixate in specific locations that provided useful information on what is relevant for task accomplishment (Neggers and Bekkering 2001; Patla and Vickers 1997, 2003; Hollands et al. 2002; Hayhoe et al. 2003). For instance, during a pointing task, gaze precedes and is directed towards the target for the whole pointing movement (Neggers and Bekkering 2001); or during locomotion tasks over cluttered terrain, fixations are directed systematically to the obstacle and end-point goal (Patla and Vickers 1997). In the case where the task is not specified *a priori* such as in the alternate foot placement situation, the spatial and temporal changes in gaze fixation patterns may reveal not only what is relevant and how vision is used to guide limb trajectory, but also may aid in understanding the search and planning process for alternate foot placement. By monitoring gaze behavior, this study will focus on the detection of relevant visual information that the CNS uses in alternate foot placement selection. The third purpose of the present study is, therefore, to identify the nature of visual information used in alternate foot placement selection.

## Method

### *Participants*

Six participants volunteered for this study (3 F and 3 M; age 21.7 years SD 2.4; height 1.71 m SD 0.10; mass 69.9 kg SD 13.9). Participants did not have any neurological, muscular, or joint disorders that could affect their performance in this study. None of the participants had any visual deficit that would require wearing glasses or lens for correction. The Office of Research Ethics at the University of Waterloo approved the procedures used in this study.

### *Protocol*

Participants walked at a self-selected pace on a raised platform (7.90 x 1.20 x 0.10 m) that contained two LCD monitors that were placed in sequence (Samsung SyncMaster™ TFT 181T Black) and embedded in a walkway (Figure 1). A piece of Plexiglas™ covered the monitors, allowing participants to step normally over them. The starting point and the location of the monitors were adjusted for each participant in order to guarantee that the entire right and left feet landed on the centre of monitors 1 and 2, respectively. A trigger mat was placed one stride before monitor 1. The trigger mat was used to control the display of the planar virtual obstacles. Six different conditions were tested: 1) AP, 2) APMLS, 3) APMLL, 4) ML, 5) MLAPS, and 6) MLAPL. The AP (anteroposterior) condition suited adjustments in the sagittal plane (lengthening/shortening the step), whereas the ML (mediolateral) condition suited adjustments in the frontal plane (widening/narrowing the step) only for the right foot on monitor 1. APMLS, APMLL, MLAPS, and MLAPL conditions combined virtual obstacles in both monitors. For example, in the APMLS condition, an AP obstacle was displayed on monitor 1, whereas a small (S) ML obstacle was displayed in monitor 2. APMLL condition is the same, except that ML obstacle in monitor 2 was large (L). Figure 1 shows all the conditions and obstacle sizes used in this experiment. Obstacles were projected at the centre of the monitor. For the AP and ML conditions, participants were required to avoid stepping with the right foot on a virtual planar obstacle displayed in the LCD monitor 1. For the remaining conditions, participants were required to avoid stepping with their right foot on the virtual planar obstacle projected in monitor 1 and with their left foot on the virtual planar obstacle projected in monitor 2. Obstacles were displayed at right heel contact (HC) on the trigger mat, which provided two steps for implementing the first adjustment. The pathway was covered with a black rubber carpet which had two holes to accommodate both monitors in order to create good contrast between the white obstacle and the black background (planar obstacles are shown in black in Figure 1 only for esthetical reasons). The edge of the monitors was also black. For the trials with no obstacle the monitor background remained completely black. Five trials were collected per condition (30 trials). In order to keep a probability of obstacle appearance equal to 30%, 70 walk-through (WT) trials were also collected. Trials were completely randomized. Participants were videotaped while performing the task.

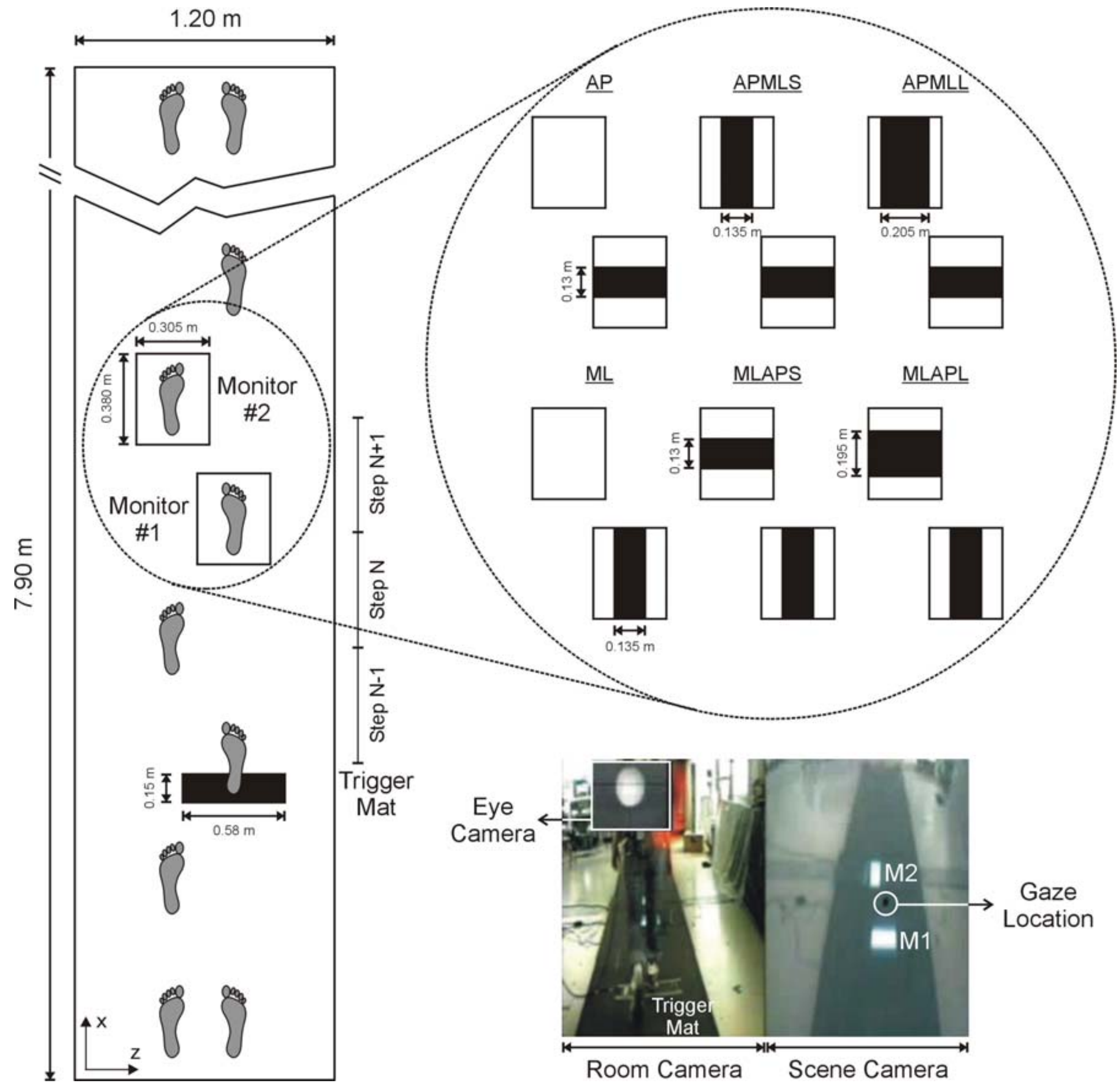


*Figure 1*. Left side shows the experimental setup including the trigger mat and both monitors 1 and 2. The top right part shows the experimental conditions used. Planar obstacles are shown in black for esthetical reasons, although during the experiment they were presented in white, and the walkway as well as the monitor background were black. The bottom right part shows one frame of the video image containing the room camera on the left, scene camera on the right, and eye camera on the top left. Gaze location is shown on the scene camera located between the monitors.

The head-mounted EyeLink system (SR Research, Osgoode, Canada) tracked the movements of the left eye at a rate of 30 Hz while the participants performed the task. This system consists of an eye camera and a scene camera. The scene camera captures the scene being viewed by the participant (Figure 1). An infrared illumination beam, which is coaxial with the optical axis of the eye camera, and the eye image are reflected from a reflective visor positioned to reflect the eye of the participant. The illumination beam generates a corneal reflection (CR) from the front surface of the cornea. The separation between the pupil center and CR is used to compute the eye line of gaze, which is projected over the scene image (Figure 1). The weight of the apparatus mounted on the head of the participant was less than 0.5 kg. The images containing the scene camera with the gaze location, eye camera, and room camera were interfaced using two digital video mixers (Videonics, model MX-1) and recorded in a DVD player at a sampling rate of 30 Hz. Ten infra-red emitting diodes (IREDs) were placed bilaterally on the following anatomical landmarks: $5^{th}$ metatarsal, heel, lateral malleolus, greater trochanter, and greater tubercle of the humerus. Three OPTOTRAK™ cameras (Northern Digital, Waterloo, Canada) positioned in front of the participants tracked the IREDs at a sampling rate of 60 Hz. Optotrak and video data were synchronized using a light emitting diode (LED) placed over the gait camera. The signal to start Optotrak data collection was also used to turn on the LED. Feet borders were traced on a sheet of paper for measuring foot length and width used in the calculation of predicted minimum foot displacement.

*Data analysis*

Kinematics data were filtered using a fourth-order zero lag low-pass digital Butterworth filter with a cut-off frequency of 6 Hz. Shoulder and hip markers were used to calculate trunk center of mass ($T_{COM}$) using anthropometric parameters provided by Winter (2005). $T_{COM}$ velocity was calculated as the first derivative of COM position (central difference procedure). Heel contact (HC) was determined by visual inspection of the foot stick figure using the OptoFix software (Mishac Kinetics). Foot placement modification vector magnitude and orientation were calculated based on ankle marker coordinates. For each obstacle trial, the AP and ML coordinates of the ankle marker at HC were subtracted from the average coordinates of the WT in order to define the relative coordinates (RC). The average values were obtained from 10 randomly selected WT trials. The norm (foot placement modification vector magnitude) and angle (foot placement modification vector orientation) of the RCs were computed as previously shown in chapters 2 and 3 (Figure 4). Vector orientation was used to define the adjustment done for each obstacle. For both feet, foot placement modification vector angles >45° to 135° and >225° to 315° were classified as long and short adjustments, respectively. For the right foot, foot placement modification vector angles from 0° to 45° and >315° to 360° were classified as lateral adjustment whereas >135° to 225° were classified as medial adjustment. For the left foot, foot placement modification vector angles from 0° to 45° and >315° to 360° were classified as medial adjustment and >135° to 225° were classified as lateral adjustment. Percentage of adjustments in each direction for each foot was calculated relative to the total number of trials the participants successfully performed.

Predicted minimum foot displacement (PMFD) was calculated as the perpendicular distance between the average foot placement and the edge of the obstacle for all four options: lateral, long, medial, and short. This measure reflects the minimum amount of foot displacement necessary to clear and avoid stepping on the virtual planar obstacle. For this calculation foot markers and average foot length and width for each participant extracted from the foot tracings were used as well as the obstacle dimensions. PMFD was calculated for obstacles in monitors 1 and 2 separately.

Maintenance of forward progression was assessed by measuring the $T_{COM}$ deviation from the straight line, which is parallel to the AP axis. $T_{COM}$ position at HC in steps N-1 and N were used to compute the maintenance of forward progression variable. Stability was determined by the relationship between $T_{COM}$ and base of support (BOS), defined by feet markers at the beginning of the double support phase for each step. The $T_{COM}$-BOS AP distance was calculated relative to the anterior margin of the BOS, defined as the line connecting the right and left fifth metatarsals. The $T_{COM}$-BOS ML distance was calculated relative to the heel marker. For right heel contact, the right heel marker was used and vice-versa for the left heel contact.

In order to identify the relative contribution of each step to final foot placement adjustment, a variable called relative adjustment (RA) was calculated as proposed by Moraes et al. (2004). This variable was calculated separately for the adjustment in monitor 1 and for the adjustment in monitor 2. This was necessary, since this variable computes the relative change based on the final change in foot placement. For the adjustment in monitor 1, RA was calculated as follows:

$$RA_{N-1} = \frac{RC_{N-1}}{RC_N} \qquad \text{Equation 1}$$

$$RA_N = \frac{\left(RC_N - RC_{N-1}\right)}{RC_N} \qquad \text{Equation 2}$$

where RA is the relative adjustment, RC is the relative coordinate, N-1 is the step before the adaptive step, and N is the adaptive step for monitor 1. For the long/short adjustments, the $RC_x$ (i.e., anteroposterior coordinate) was used for RA calculation, and $RC_z$ (i.e., mediolateral coordinate) was used for the RA calculation for the lateral/medial adjustments.

For the adjustment in monitor 2, RA was calculated as follows:

$$RA_{N-1} = \frac{RC_{N-1}}{RC_{N+1}} \qquad \text{Equation 3}$$

$$RA_{N} = \frac{(RC_{N} - RC_{N-1})}{RC_{N+1}} \qquad \text{Equation 4}$$

$$RA_{N+1} = \frac{(RC_{N+1} - RC_{N})}{RC_{N+1}} \qquad \text{Equation 5}$$

where N+1 is the adaptive step for the monitor 2.

The gaze data was analyzed frame-by-frame using a DVD player and a television. Within each step starting with right HC on the trigger mat, gaze fixations were determined. The initial and final frame of each step was defined based on kinematic data from the OPTOTRAK system. A fixation was defined as the maintenance of the gaze location (Figure 1) in the same spot for at least three frames in sequence (~100 ms). This value was the same as previously reported by Patla and Vickers (1997, 2003) and Hollands et al. (2002). Fixations were classified into four types: 1) area stepped, 2) areas other, 3) area-to-avoid, and 4) area ahead. *Area stepped* was the spot were the participant stepped in order to avoid the obstacle. *Areas other* were the spots near the obstacle where participants chose not to step and included all other three options for alternate foot placement. *Area-to-avoid* was defined by the obstacle dimensions. *Area ahead* was defined as a spot on the ground that remained unchanged and was always ahead of the monitor. The percentage of the fixation length within each step was calculated relative to step duration. In addition, the frequency distribution of the fixation lengths was computed for bins of 100 ms. The final parameter measured was the time correspondent to the end of fixation relative to HC of alternate foot placement. For the fixations relative to monitor 1, end of fixation was computed relative to right alternate foot placement; whereas for the fixations relative to monitor 2, end of fixation was calculated relative to left alternate foot placement.

*Statistical analysis*

Two-way (Condition x Choice) chi-square ($\chi^2$) analyses were carried out for the choices in order to identify whether or not the presence of a second obstacle affected the alternate foot placement choice in the first one and, also, if the increase in obstacle size in monitor 2 affected the alternate foot placement choice. For the former objective, two $\chi^2$ analyses were performed combining the conditions with the same first obstacle (AP/APMLS/APMLL and ML/MLAPS/MLAPL). For the latter objective, two $\chi^2$ analyses were also computed combining the conditions with the second obstacle having the same orientation (APMLS/APMLL and MLAPS/MLAPL). In order to identify whether or not PMFD was different between options, a one-way ANOVA (Option: long, short, lateral, and medial) with repeated measures was carried out for each obstacle and monitor separately. Effect of the presence of a second obstacle on alternate foot placement for the first obstacle for the foot placement modification vector magnitude and maintenance of forward progression was analyzed using a one-way repeated measure ANOVA (Condition: all six conditions) for each dependent variable. For the second obstacle, the effect of obstacle size on the foot placement modification vector magnitude was analyzed using a one-way repeated measure ANOVA (Condition: APMLS, APMLL, MLAPS, and MLAPL). $T_{COM}$-BOS AP and ML distances were statistically analyzed using a two-way repeated measures ANOVA (Conditions: all six conditions x Step: N-1 and N) for each dependent variable. Relative adjustment was statistically analyzed using a two-way ANOVA (Condition x Step) for each obstacle separately. For the first obstacle, all six conditions and two steps (N-1 and N) were included; whereas for the second obstacle, four conditions (APMLS, APMLL, MLAPS, and MLAPL) and three steps (N-1, N, and N+1) were included. The dependent variables were averaged across trials for each participant and the average value was used for statistical analyses. When main effects or interaction effects were found, least-squares means post-hoc analyses were carried out to identify the differences. Spearman rank order correlations between alternate foot placement choices in step N+1, and $T_{COM}$ velocity in all three directions for steps N-1 and N were carried out. Alpha value was set at 0.05.

## Results

### Kinematic analysis

*What is the minimum foot displacement for the first and second obstacles?*

For the first obstacle, the one-way ANOVA (Option: long, short, lateral, and medial) for the AP and ML obstacles revealed a main effect of option (AP: $F_{3,15} = 21.8$, $p < 0.0001$; ML: $F_{3,15} = 292.8$, $p < 0.0001$). For both obstacles, post-hoc analysis identified that all pairwise comparisons were significantly different, except the comparison between lateral and medial options. For the AP obstacle, PMFD for the short option (16.9 cm) was smaller than medial/lateral options (20.7 and 21.2 cm, respectively), which in turn were smaller than the long option (25.4 cm). For the ML obstacle, the smallest PMFD was identified for the medial/lateral options (12.2 and 12.4 cm, respectively), followed by short (29.4 cm) and long options (37.9 cm).

For the second obstacle, the one-way ANOVA (Option: long, short, lateral, and medial) for the ML small and large obstacles revealed main effects of option (MLS: $F_{3,15} = 136.97$, $p < 0.0001$ | MLL: $F_{3,15} = 96.38$, $p < 0.0001$). For both obstacles, the post-hoc analyses showed that all pairwise comparisons were significantly different, except between long and short options. The smallest PMFD was observed for the medial option (MLS =

10.7 cm; MLL = 14.2 cm), followed by the lateral option (MLS = 14.2 cm; MLL = 17.7 cm) and then by long/short options (35.1 cm and 32.1 cm, respectively). For the AP small and large ANOVAs, only the latter one revealed a main effect of option ($F_{3,15} = 6.69$, $p = 0.0044$). The smallest PMFD was found for the medial option (19.2 cm), followed by the lateral/short options (22.7 cm and 22.9 cm, respectively) and the long option (25.9 cm). For the AP small obstacle, the PMFD were equal to 19.2 cm, 19.6 cm, 22.6 cm, and 22.7 cm for the medial, short, long, and lateral options, respectively.

*Does the presence of a second obstacle affect the selection and/or the magnitude of alternate foot placement in the first obstacle?*

For both AP and ML obstacles in the first monitor, the dominant choice was lateral (Figure 2). The two-way $\chi^2$ analyses (Condition: AP/APMLS/APMLL or ML/MLAPS/MLAPL x Choice: long, short, lateral, and medial) for the first obstacle showed that there was no difference among the conditions for the selection of the alternate foot placement when the second obstacle was present (Figures 2 and 3).

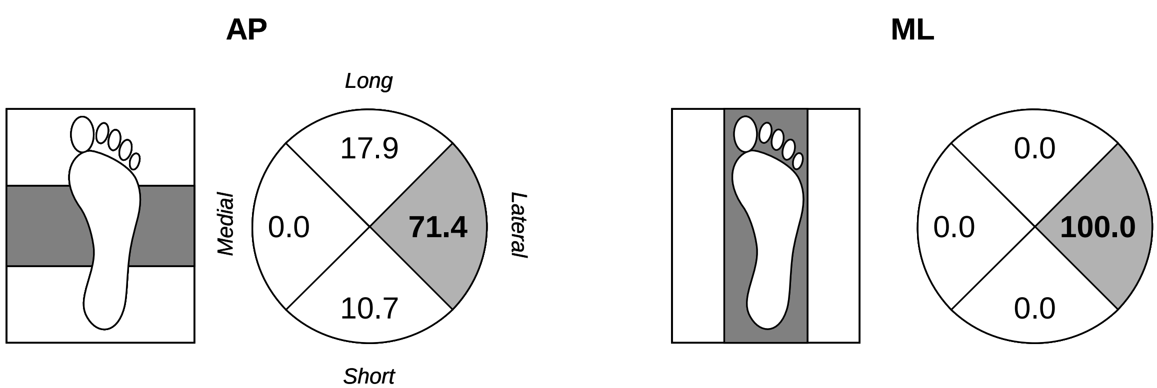


*Figure 2*. Choice percentage for the conditions with only one obstacle.

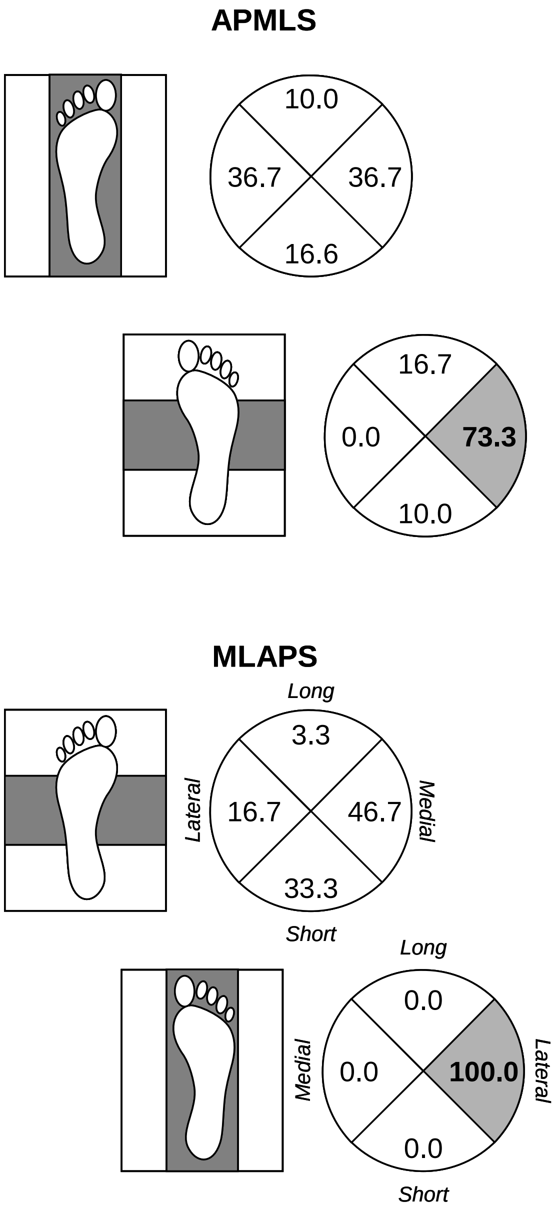


*Figure 3*. Choice percentage for the conditions with two obstacles.

Figure 4 shows the foot placement modification vector distribution. The foot displacement in step N seems to be unaffected by the presence of a second obstacle for the conditions with the same first obstacle. In fact, the one-way ANOVA (Condition: all six conditions) for the foot placement modification vector magnitude for the first obstacle revealed a main effect of condition ($F_{5,25} = 10.98$, $p < 0.0001$). Foot placement modification vector magnitude was larger for the AP (22.1 cm), APMLS (21.9 cm), and APMLL (22.8 cm) than for the ML (16.8 cm), MLAPS (18.4 cm), and MLAPL (18.0 cm) conditions.

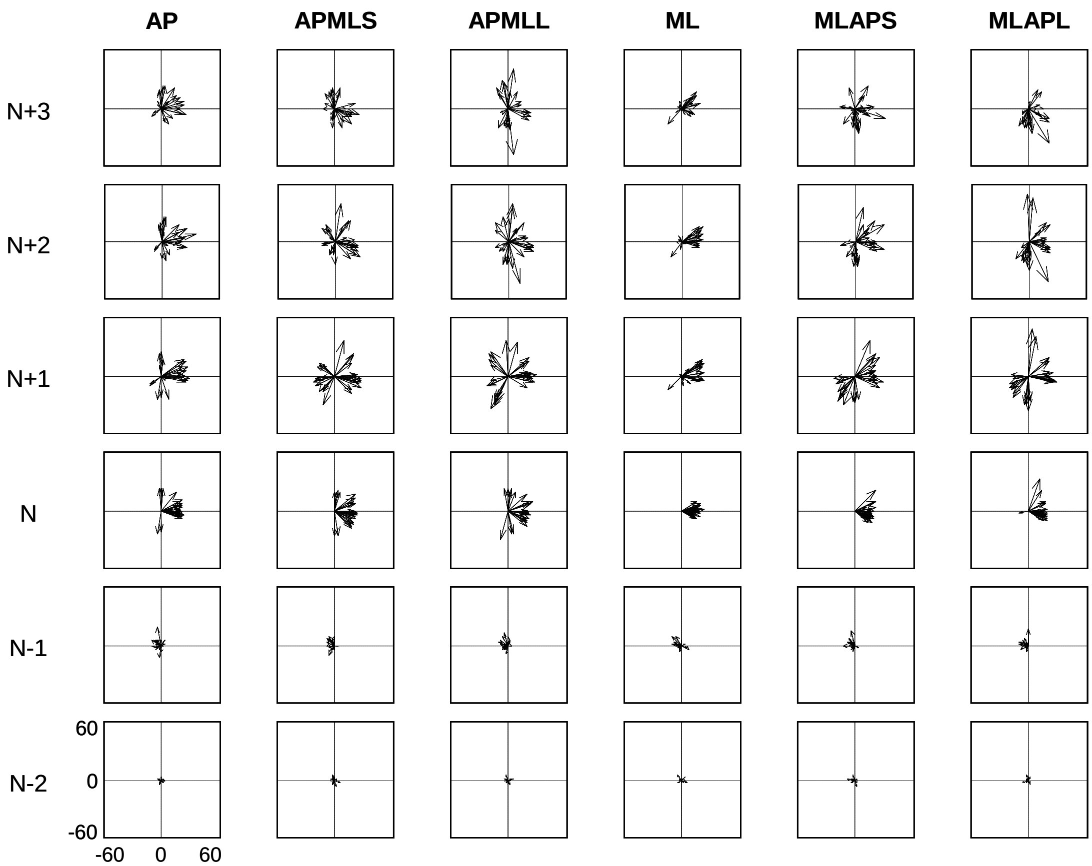


*Figure 4*. Foot vector distribution for all six conditions from the step on the trigger mat (N-2) to two steps after the second obstacle (N+3).

*Is there a dominant choice for alternate foot placement with the second obstacle?*

Although the percentages were quite similar among conditions, there was no dominant choice for the second obstacle (Figure 3). Three of the participants systematically chose a medial option for the second obstacle independent of obstacle size and orientation. One participant chose to step laterally and another one chose to shorten the step when faced with the second obstacle. For one participant in the conditions where the second obstacle was AP, the dominant choice was shortening the step, while when the second obstacle was

ML, the dominant choice was lateral for the small obstacle and long for the large obstacle. In summary, five participants showed a systematic dominant choice for the second obstacle independent of its size and orientation. However, this dominant choice was not consistent among participants.

*Does the increase in the second obstacle size affect the alternate foot placement selection and/or foot placement modification vector magnitude?*

The selection of alternate foot placement for the second obstacle was not different between APMLS and APMLL and between MLAPS and MLAPL conditions (Figure 3). The one-way ANOVA (Condition: APMLS, APMLL, MLAPS, and MLAPL) identified no main effect of condition for the foot placement modification vector magnitude. The average foot placement modification vector magnitude was similar among conditions (APMLS = 24.1 cm; APMLL = 26.0 cm; MLAPS = 25.0 cm; MLAPL = 24.6).

*Does the presence of a second obstacle affect maintenance of forward progression?*

A one-way repeated measure ANOVA (Condition: all six conditions and WT) identified a main effect of condition ($F_{1,29} = 7.62$, $p < 0.0001$) for the maintenance of forward progression. Least-squares means post hoc analysis revealed that all experimental conditions increased the deviation to the right by 4.5° with respect to WT, due to the lateral preference in the first obstacle. In addition, no difference between conditions with one and two obstacles was found.

*Does the presence of a second obstacle affect stability?*

The two-way repeated measures ANOVA (Condition: all six conditions and WT x

Step: N-1 and N) for the $T_{COM}$-BOS AP distance revealed only a main effect of condition ($F_{6,30} = 4.99$, $p = 0.0012$). Least squares means post hoc analysis showed that $T_{COM}$-BOS AP distance decreased similarly for all experimental conditions compared to the WT. In other words, independent of the presence of a second obstacle, stability was equally reduced for all experimental conditions. For the $T_{COM}$-BOS ML distance, the two-way repeated measures ANOVA (Condition: all six conditions and WT x Step: N-1 and N) identified main effects of condition ($F_{6,30} = 19.49$, $p < 0.0001$) and step ($F_{1,35} = 216.70$, $p < 0.0001$) as well as an interaction effect ($F_{6,35} = 5.56$, $p = 0.0004$). For the interaction effect, no difference was observed among conditions in step N-1, but all experimental conditions showed an increased $T_{COM}$-BOS ML distance as compared to the WT in step N, due to the lateral choice preference.

*Do the changes in foot placement in step N-1 contribute to the alternate foot placement in step N?*

The two-way ANOVA (Condition: all six conditions x Step: N-1 and N) for the relative adjustment identified a main effect of step ($F_{1,30} = 392.24$, $p < 0.0001$). Alternate foot placement was implemented in step N; step N-1 did not contribute to changes in step N (Figure 5A).

*Do the changes in foot placement in step N-1 and N contribute to alternate foot placement in step N+1?*

For this statistical analysis, only 5 participants were included since one participant systematically chose lateral adjustments for both obstacles. For the case of lateral choice in both obstacles, relative adjustment of step N is always in the opposite direction compared to the relative adjustment in step N+1. Then, the relative adjustment for this participant in step N was always negative, substantially increasing the variability. For all other participants, relative adjustment in step N was always positive. The two-way ANOVA (Condition: APMLS, APMLL, MLAPS, and MLAPL x Step: N-1, N, and N+1) identified a main effect of step ($F_{2,30} = 16.09$, $p < 0.0001$). Post-hoc analysis revealed that irrespective of the obstacle condition the relative adjustment was different among the three steps tested (Figure 5B). Step N-1 did not contribute to adjustment in step N+1 (-8.0%). Most of the contribution came from step N (68.0%) followed by step N+1 (40.0%).

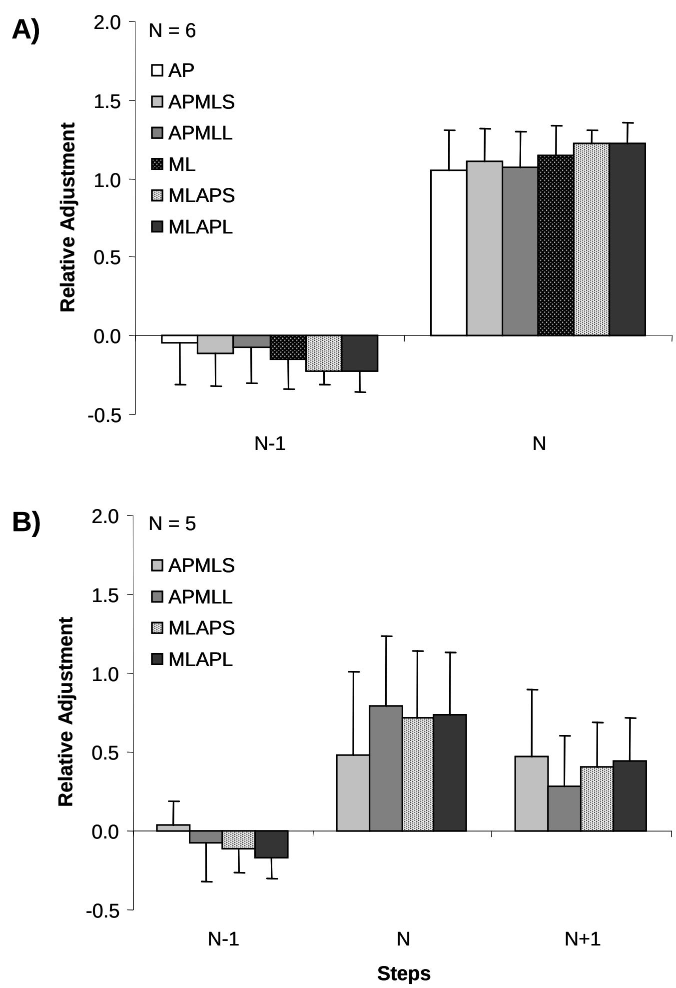


*Figure 5*. Mean and standard deviation for the relative adjustment for the A) first obstacle (N = 6) and B) second obstacle (N = 5).

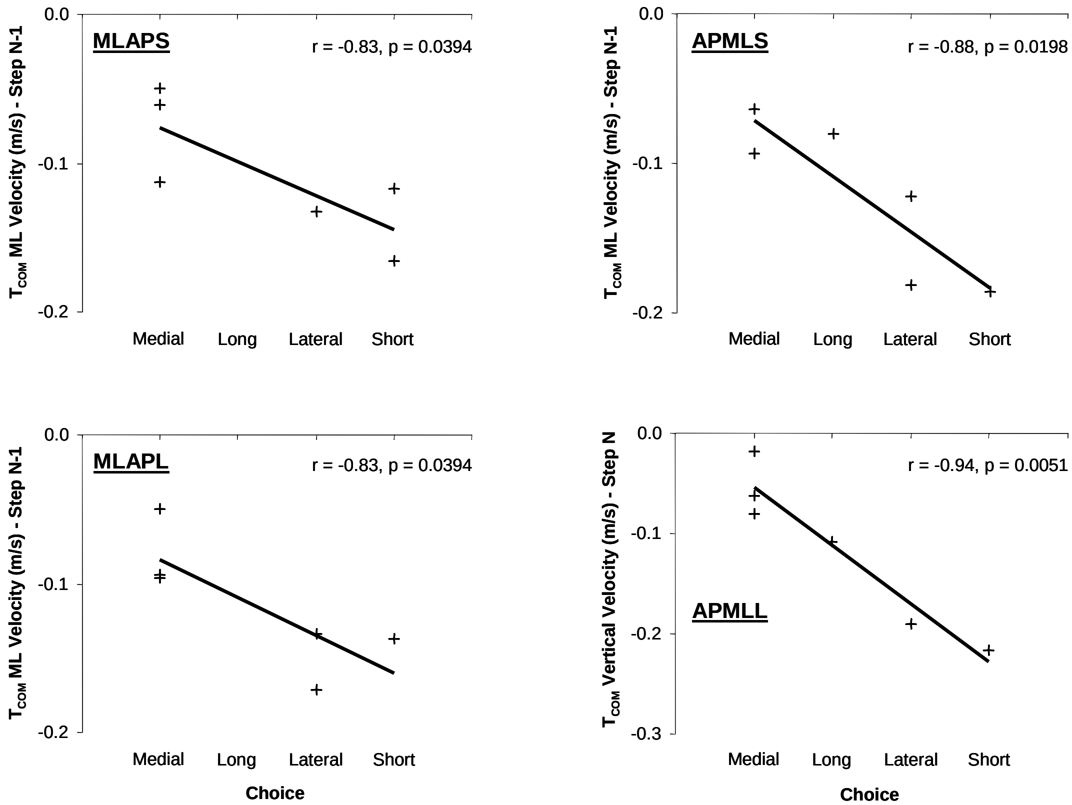


*Figure 6*. Plots of the trunk center of mass ($T_{COM}$) velocity versus the alternate foot placement choice for the second obstacle. For the MLAPS, MLAPL, and APMLS conditions the $T_{COM}$ velocity in the ML direction in step N-1 is shown. For the APMLL condition, the $T_{COM}$ velocity in the vertical direction in step N is shown. Spearman correlation values with respective probability values are shown for each plot.

*Is there any association between alternate foot placement choice in step N+1 and $T_{COM}$ velocity in previous steps?*

For three conditions (APMLS, MLAPS, and MLAPL), $T_{COM}$ ML velocity in step N-1 significantly correlated with the alternate foot placement choices in step N+1 (Figure 6). This correlation indicates that for the medial adjustment, $T_{COM}$ ML velocity reduced in step N-1 to facilitate the body displacement to the right. This shows an increase in $T_{COM}$ ML velocity for the medial adjustments facilitating the body displacement to the right. For the APMLL condition, the correlation between $T_{COM}$ ML velocity in steps N-1 and N just failed to achieve statistical significance (p = 0.08). However, the $T_{COM}$ vertical velocity in step N correlated with the alternate foot placement choice in step N+1 ($r = -0.94$, $p = 0.0051$). In addition, $T_{COM}$ ML velocity in step N significantly correlated with the alternate foot placement in step N+1 ($r = -0.94$, $p = 0.0054$) for the MLAPS condition.

Gaze analysis

Gaze fixations were classified into four categories and they accounted for all fixations observed in the present study. The instants when participants were not fixating in one of these four areas, they were either making a saccade or the eyes were blinking and the cursor was missing. For each participant, only the fixations that were present in at least three trials per condition were used for the average calculations presented in the next sections. This criterion was used to guarantee that only consistent gaze behaviors would be considered for discussion.

Gaze analysis revealed an unexpected result. Interestingly, gaze behavior was different among participants relative to the final gaze fixation, enabling the establishment of two groups: distant and local anchor groups. Three participants systematically anchored their gaze at a point on the ground ahead of the obstacle region (distant anchor group). The other three participants directed their gaze to the area stepped in the alternate foot placement (local anchor group). Figure 7 illustrates the gaze behavior for steps N-1 and N for one participant of the local anchor group, and for one participant in the distant anchor group for conditions involving the avoidance of one obstacle. Fixations on the area stepped dominated step N for the local anchor group; whereas fixations on the area ahead dominated the same step for the distant anchor group. The gaze behavior for conditions with two obstacles is illustrated in Figure 8. The distant anchor group fixated on a point ahead in step N+1; whereas local anchor group fixated on the area stepped in both steps (i.e., N and N+1). Because of this finding, no statistical analysis could be carried out for the gaze data since three participants in each group would not be enough for any statistical consideration. Therefore, the data is qualitatively described.

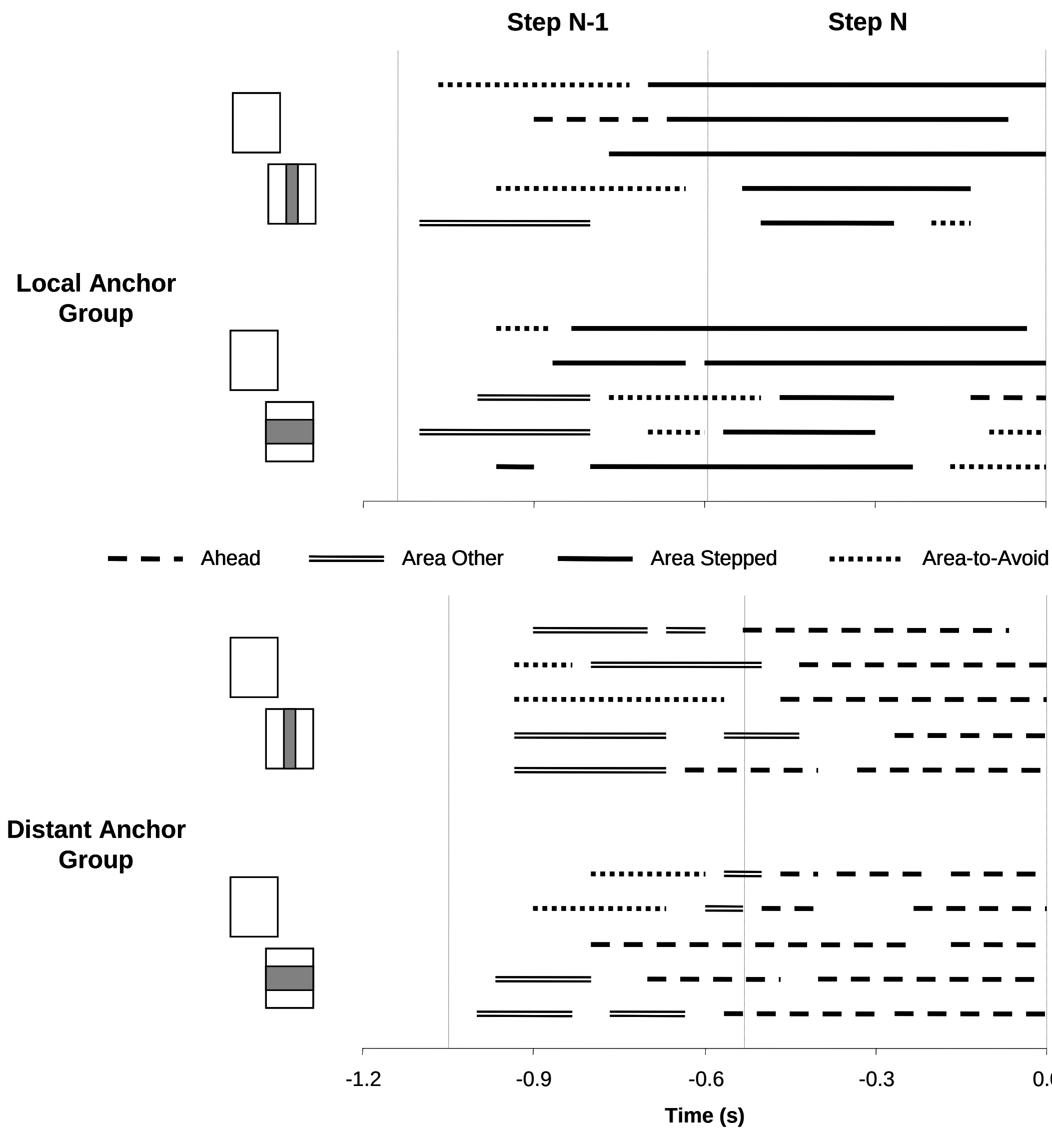


*Figure 7*. Gaze fixations on different areas for the conditions with one obstacle for one participant in the local anchor group (top), and for one participant in the distant anchor group (bottom). Five trials per condition are shown. Each line length indicates the fixation duration and each line style corresponds to fixations in different areas. Dashed vertical lines indicate the mean step duration interval. The negative time indicates the time before right heel contact for alternate foot placement for the obstacle in monitor 1.

For conditions with one obstacle, participants of the distant anchor group fixated on the area ahead in 93.4% of the trials. For conditions with two obstacles, they fixated on the point ahead in 26.7% and 85.0% of the trials for the first and second obstacles, respectively. For conditions with one obstacle, participants of the local anchor group fixated on the area stepped in 93.4% of the trials. For conditions with two obstacles, they fixated on the area stepped in 83.3% and 85.0% of the trials for the first and second obstacles, respectively.

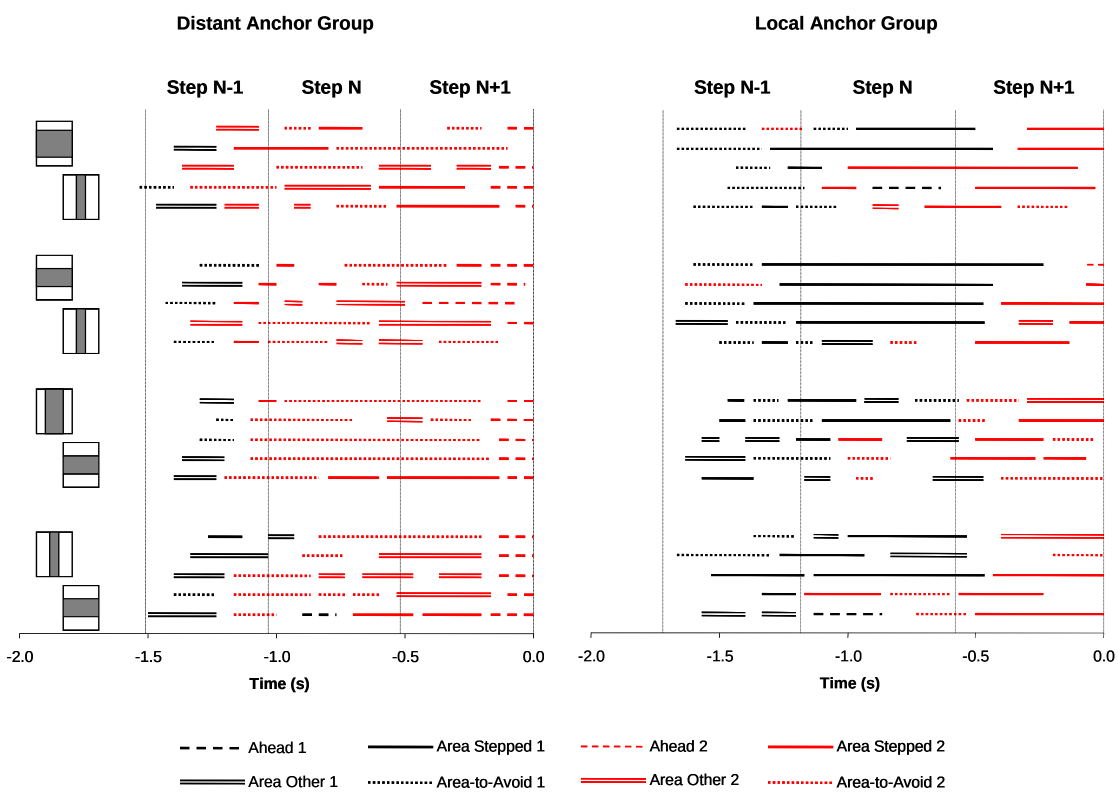


*Figure 8*. Gaze fixations on different areas for the conditions with two obstacles for one participant in the distant anchor group (left), and for one participant in the local anchor group (right). Five trials per condition are shown. Each line length indicates the fixation duration and each line style corresponds to fixations in different areas. Numbers 1 and 2 in front of the fixation area code indicate the fixations relative to the first and second obstacles, respectively. Dashed vertical lines indicate the mean step duration interval. The negative time indicates the time before left heel contact for alternate foot placement for the obstacle in monitor 2.

For the conditions with one obstacle, the highest percentage of gaze fixation (~60%)

in step N for the distant anchor group appeared for the area ahead; whereas for the local anchor group it appeared for the area stepped (Figure 9). Only in these two categories did all three participants of each group consistently fixate their gazes. The fixations in other areas were quite inconsistent among participants within each group. For conditions with two obstacles, the local anchor group fixated on the area stepped for both obstacles approximately 60% of the time in steps N and N+1 (obstacles 1 and 2, respectively) (Figure 10). Again, the fixations in step N-1 were quite inconsistent, with the exception of distant local group, where all three participants fixated on the area stepped in obstacle 1 (~25%). For the distant anchor group, the fixations on area ahead dominated step N+1, followed by fixations on area other. In step N, the distant anchor group systematically fixated in area other for the second obstacle.

*How long are the fixations for the distant and local anchor groups?*

For the distant anchor group, slightly more than half of the fixations on the area ahead were no longer than 200 ms for the conditions with one obstacle (Figure 11). For the local anchor group, fixations on the area stepped were usually quite long (> 500 ms) for conditions with one obstacle. For conditions with two obstacles, the distant anchor group showed a predominance of fixations on area ahead and area other with a length of usually less than 200 ms (Figure 12) for the second obstacle. For the distant anchor group, the number of fixations was smaller for the first obstacle than for the second obstacle. The local anchor group exhibited a predominance of fixations on area stepped in both obstacles. For the first obstacle, fixations on area stepped were equally distributed ranging from 100 to 500 ms. For the second obstacle, fixations on area stepped were more concentrated, in the range of 200 to 400 ms.

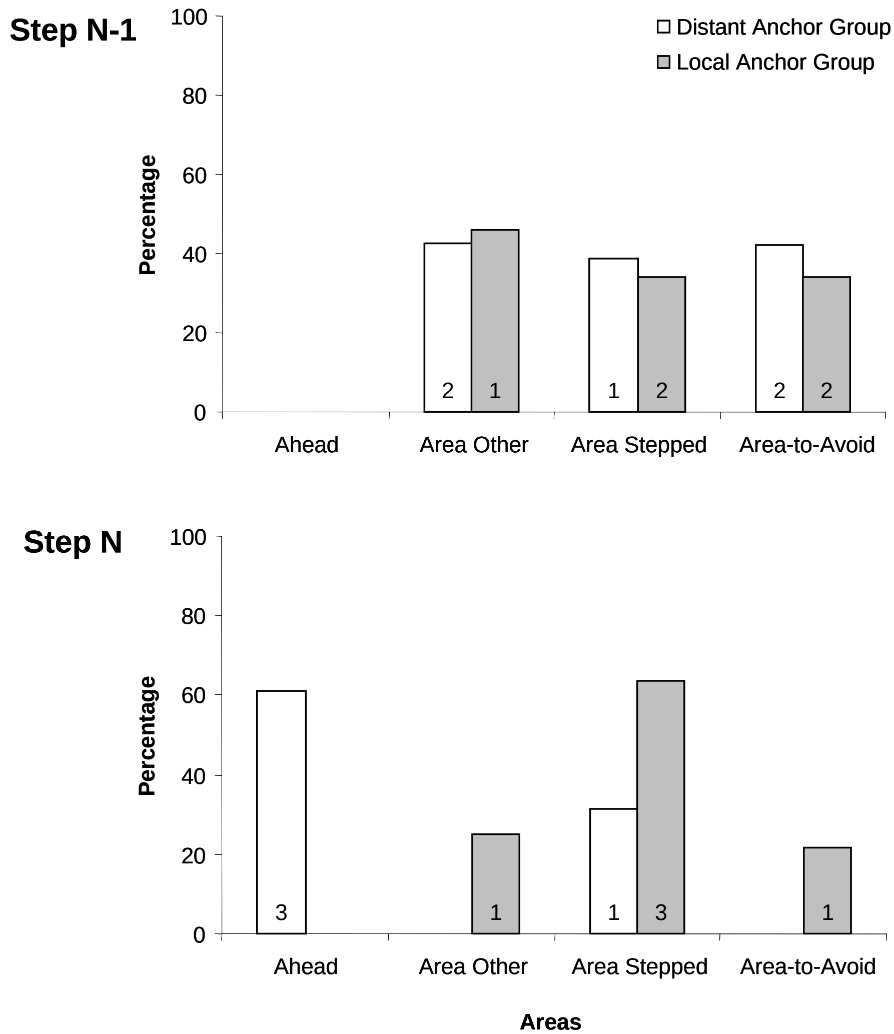


*Figure 9*. Mean percentage of gaze fixation in different areas relative to step duration for the distant and local anchor groups for the conditions with one obstacle. The numbers inside each bar indicate the number of participants who exhibited the fixation in the respective step. Since no noticeable difference was observed between conditions, the mean value was calculated across conditions.

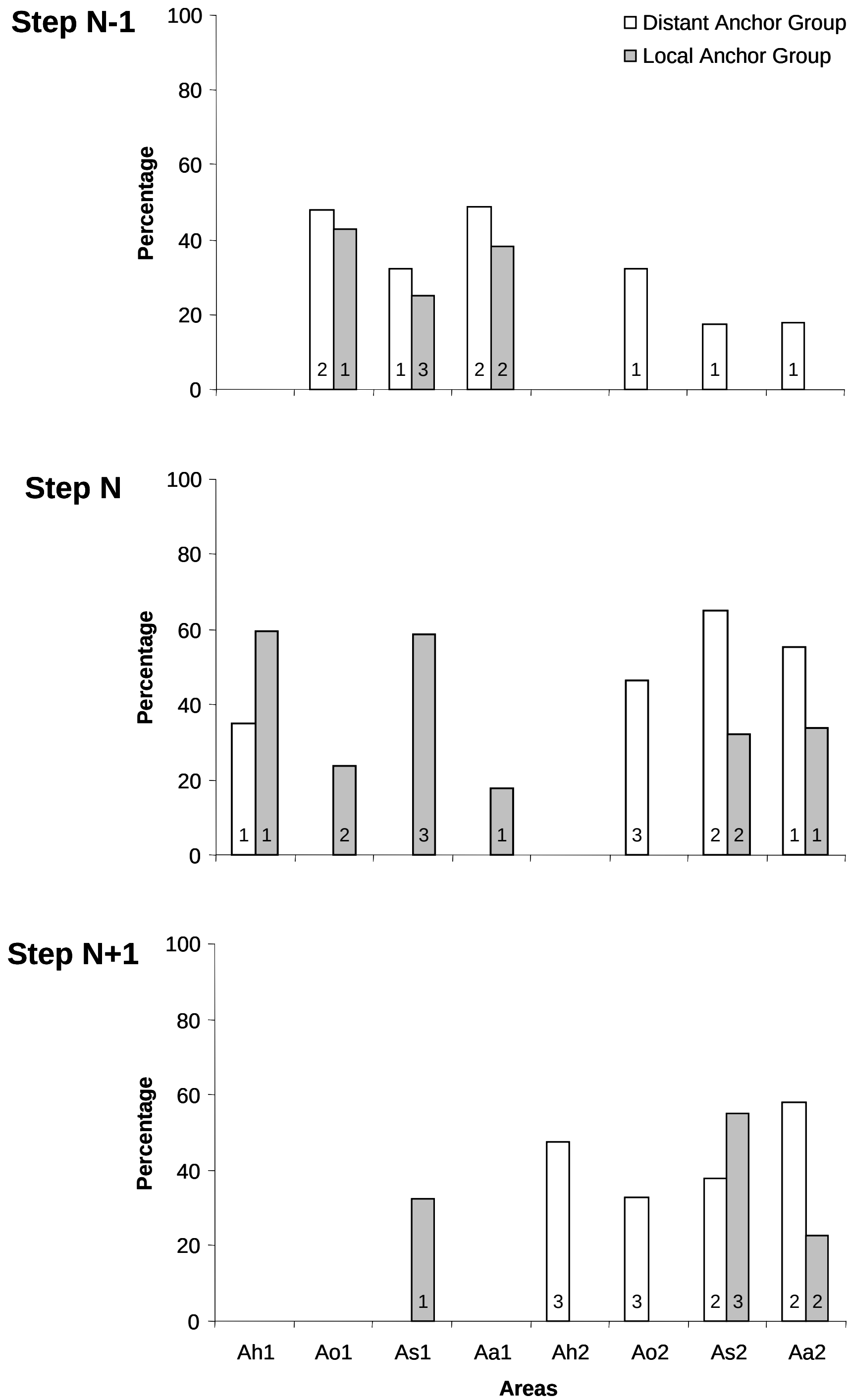


*Figure 10*. Mean percentage of gaze fixation in different areas relative to step duration for the distant and local anchor groups for the conditions with two obstacles. The numbers inside each bar indicate the number of participants who exhibited the fixation in the respective step. Since no noticeable difference was observed between conditions, the mean value was calculated across conditions. Numbers 1 and 2 in front of the areas' codes in the horizontal axis relate to the first and second obstacles, respectively. (Ah = ahead; Ao = area other; As = area stepped; Aa = area-to-avoid)

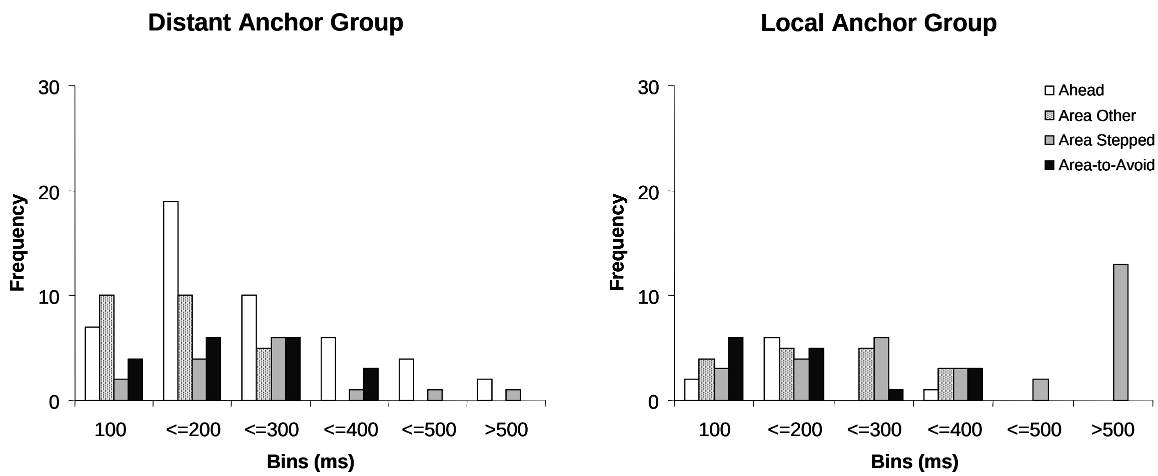


*Figure 11*. Frequency distributions of the fixation duration for both distant (left) and local (right) anchor groups for each fixation area for the conditions with one obstacle. Data are presented across conditions.

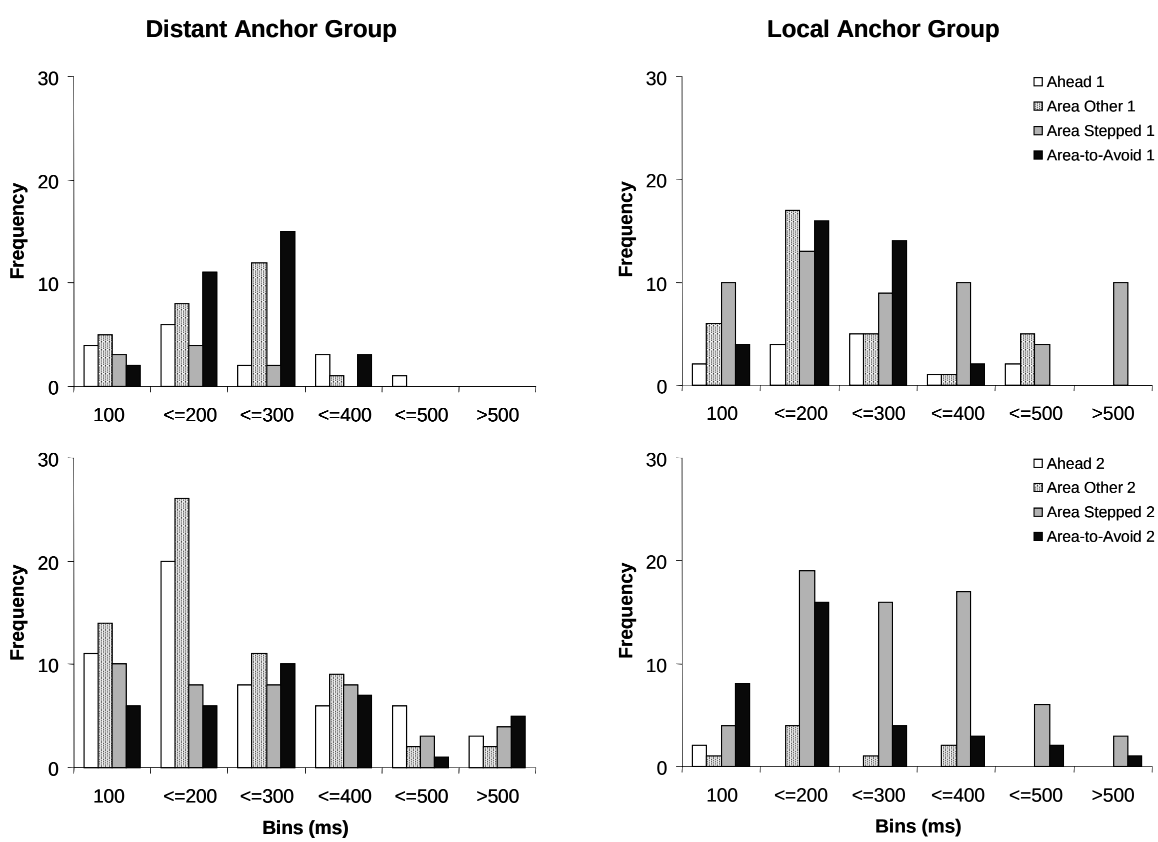


*Figure 12*. Frequency distributions of the fixation duration for both distant (left) and local (right) anchors groups for each fixation area for the conditions with one obstacle. Top graphs are the distribution of the fixations for the first obstacle. Bottom graphs are the distribution of the fixations for the second obstacle. Data are presented across conditions.

*When does the end of gaze fixation occur for the distant and local anchor groups relative to heel contact for alternate foot placement?*

Participants in the local anchor group fixated at the area stepped until approximately 145 ms (mean value computed from Table 1) before heel contact for the final alternate foot placement. The distant anchor group fixated on the area ahead until approximately 50 ms before heel contact for the final alternate foot placement (mean value computed from Table 1).

*Table 1*. Mean end of fixation in milliseconds (ms) across conditions. Conditions with one obstacle and two obstacles were grouped separately. For conditions with two obstacles, end of fixation was calculated relative to heel contact for alternate foot placement for steps N and N+1 for fixations in the first and second obstacles, respectively. Negative values indicate that fixations terminated before heel contact for alternate foot placement. The numbers in parenthesis indicate the number of participants who consistently exhibited the fixation behavior.

| Conditions | Fixations | End of Fixation (ms) | |
|---|---|---|---|
| | | Distant Anchor Group | Local Anchor Group |
| One Obstacle | Ahead | -78.0 (3) | 0.0 (0) |
| | Area Other | -571.8 (2) | -508.0 (1) |
| | Area Stepped | -274.0 (1) | -157.8 (3) |
| | Are-to-Avoid | -751.1 (2) | -458.8 (2) |
| Two Obstacles | Ahead 1 | -232.2 (1) | -143.3 (1) |
| | Area Other 1 | -661.5 (2) | -507.5 (2) |
| | Area Stepped 1 | -576.7 (1) | -246.9 (3) |
| | Are-to-Avoid 1 | -682.2 (2) | -635.8 (2) |
| | Ahead 2 | -21.9 (3) | 0.0 (0) |
| | Area Other 2 | -492.2 (3) | 0.0 (0) |
| | Area Stepped 2 | -488.8 (2) | -133.3 (3) |
| | Are-to-Avoid 2 | -467.3 (2) | -274.0 (2) |

## Discussion

This study addresses two issues associated with alternate foot placement. First, it looks at the generality of alternate foot placement determinants by having participants avoid two virtual planar obstacles in the travel path. Second, it addresses the nature of the visual information used for selecting and planning alternate foot placement by monitoring gaze behavior. The following discussion is organized to address the three major conclusions from the present study: 1) alternate foot placement selection for the first obstacle is guided by stability, minimum foot displacement, and facilitation of the subsequent alternate foot placement, 2) alternate foot placement is planned globally when more than one obstacle has to be avoided, 3) individuals use two gaze behavior strategies.

*Alternate foot placement selection for the first obstacle is guided by stability and minimum foot displacement*

The presence of a second obstacle clearly increased the complexity of the task. This increase in complexity generated a more variable behavior among participants for selection of alternate foot placement for the second obstacle. Nevertheless, the dominant choice for the first obstacle was very consistent and it was unaffected either by the presence of a second obstacle or by the size increase of the second obstacle. The lateral dominant choice for the ML obstacle coincided with the minimum foot displacement, although a medial option would have required the same amount of foot displacement. However, as discussed in chapter 3, lateral options are more stable than medial ones. The difference between PMFD and the actual foot displacement was equal to 4.1 cm, indicating that participants placed the foot just at the edge of the obstacle. The lateral preference for the AP obstacle did not coincide with the minimum foot displacement, which was for the short option (16.9 cm). However, the lateral choice represented the second minimum foot displacement (21.2 cm) and the difference between the PMFD and the actual foot displacement was equal to

0.9 cm. Again, as previously discussed, the lateral preference over the medial option was based on stability. Therefore, for the ML and AP obstacles, alternate foot placement selection was mainly based on stability and minimum foot displacement. However, minimum foot displacement contribution was smaller for the AP obstacle than for the ML obstacle for selecting alternate foot placement. Forward progression seemed to be less important since it created a deviation of about 4.5° from the straight goal. Although an average deviation of 4.5° may seem quite small, model simulations have shown that deviations higher than 5.0° may have a great impact in alternate foot placement selection and, consequently, may move the gait trajectory from the end-point goal (Bahrami and Patla 2005).

*The dominant lateral choice for the first AP obstacle facilitates response to the second obstacle*

For the first AP obstacle, lateral adjustment preference over short option may be due to the presence of the second obstacle, although when only one obstacle was present, lateral adjustment was also dominant. It is possible that short adjustment was not chosen because it could make it difficult to implement the necessary changes for the second obstacle. Short adjustment is accompanied by a reduction in the AP center of mass velocity, as shown in chapter 3. This overall velocity reduction may be undesirable since it would create the necessity of compensating during the push-off to clear the second obstacle. The option of shortening both steps to avoid both obstacles may also be undesirable, since the distance between the obstacles could be small and a very precise foot placement would be necessary. Therefore, for the AP obstacle, selection of alternate foot placement was dictated also by facilitating response to the second obstacle, followed by stability and minimum foot displacement.

*Half of the participants selected a route that avoided the crowded area the two obstacles represented*

For the second obstacle, the dominant choices were in the ML direction (i.e., lateral and medial choices). In all conditions with a second obstacle, the choices in the ML direction corresponded to more than 60% of the trials. For APMLS and APMLL conditions, the medial option represented the minimum foot displacement (10.7 cm and 14.2 cm, respectively), followed by the lateral option (14.2 cm and 17.7 cm, respectively). Changes in the AP direction would result in foot displacements greater than 30 cm. Only one participant systematically chose the short option for these two obstacles (i.e., MLS and MLL). However, this participant placed the foot just after the transition point between lateral and short adjustments (i.e., 229.4° and 244.0° for the APMLS and APMLL, respectively) and, consequently, the amount of foot displacement was reduced by approximately 25.0 cm. For the MLAPL condition, the medial option represented the minimum foot displacement, followed by lateral and short options. No difference was found among options for the MLAPS condition, although the average value for the PMFD for the medial option was the smallest one.

The presence of a second obstacle revealed at least two different strategies used for adapting gait on cluttered terrain. First, three participants systematically chose lateral and medial adjustments for the first and second obstacles, respectively. Although medial choice represented the smallest foot displacement for the second obstacle for APMLS and APMLL conditions, the actual foot displacement was much higher than the predicted one (~13.0 cm). This suggests that these three participants were not trying to minimize foot displacement for the second obstacle. Rather, they planned their movements to avoid the crowded area represented by both obstacles as suggested by Patla et al. (2004). In their study, Patla et al. (2004) modeled route selection over complex terrain. They found that the model that better predicted route selection was one that searched for routes that would avoid the crowded areas. Second, the other three participants seemed to minimize foot displacement. The average difference between PMFD and actual foot displacement was equal to 0.7 cm. However, for one of the participants the dominant choices were lateral for both obstacles; for another the dominant choice was short, but the left foot was placed just after the transition point between lateral and short options. In both cases, step width was substantially increased and this may not necessarily represent a more economical movement, since a great change in ML velocity to redirect center of mass would be necessary from step N to step N+1. Donelan et al. (2001) have shown that most of the metabolic costs (i.e., oxygen consumption) associated with increase in step width relate to redirecting the center of mass velocity from one stance limb to the next. Therefore, although three participants clearly decided to use a strategy that allowed them to avoid the crowded area, the strategy or strategies used by the other three participants are unclear. It is possible that minimization of foot displacement for the second obstacle was not the primary goal, but rather resulted due to some undefined strategy.

*Alternate foot placement is planned globally when more than one obstacle has to be avoided*

Two findings support the notion that movements were planned globally. First, relative adjustment was greater in step N than in step N+1. This suggests that modifications in step N contributed substantially to the adjustments in step N+1. Second, $T_{COM}$ ML velocity in step N-1 was modulated according to the alternate foot placement in step N+1. Although foot placement did not change for step N-1, changes in $T_{COM}$ velocity were implemented to facilitate alternate foot placement in step N+1. Therefore, since changes in previous steps (N and N-1) were related to alternate foot placement in step N+1, it is reasonable to suggest that alternate foot placements were planned globally as opposed to online. This conclusion disputes Fajen and Warren (2003), who proposed that obstacle avoidance is an online process and that path planning is unnecessary. However, recent work by Patla et al. (2004) suggests that route selection in a cluttered environment involves path planning. Rietdyk and Patla (1994) provided further evidence of global planning as opposed to online control. In their study, participants were requested to make changes in step length in only one or two steps while running. They concluded that the requirements of a subsequent step cycle alter the gait modifications employed to complete the current step cycle. In general, the modifications were different not only as a result of altered foot placement during the second step, but they were dependent also on the location of the second foot placement (i.e., lengthening versus shortening).

*Individuals seemed to use two gaze behavior strategies*

One interesting finding of this study was that more than one gaze behavior strategy emerged. Half of the participants systematically fixated on the area stepped on during the adaptive step (local anchor group), while the remainder fixated on a spot just ahead of the monitor area (distant anchor group). Intuitively one would try to establish a relationship between one of the anchor groups and the three participants who chose always a medial alternate foot placement for the second obstacle. However, such relationship was inexistent since the participants who chose medial adjustments were not in the same gaze group. The local and distant anchor groups fixated on the area stepped on until approximately 145 ms and 50 ms, respectively, before landing the foot (Table 1), then moved their eyes to another location or simply started looking to the end point of the walkway. Therefore, both group participants guided foot placement online during the adaptive step.

By anchoring the gaze on a spot ahead, the distant anchor group probably used their peripheral visual field--more precisely the lower visual field--for planning alternate foot placement. Crowe et al. (2000) showed that in a maze solution task, the number of turns in the maze had a negative effect on the distance traveled by the eye (measured from fixation-to-fixation points), suggesting that "saccades may "cut corners" and skip over path turns" (p.819). This suggests that peripheral vision was used to analyze the path interval within the maze. Several studies have suggested that the lower visual field has a pronounced advantage over the upper visual field for controlling visually guided movements such as pointing, interception of moving targets, reaching and grasping (Danckert and Goodale 2001, 2003; Brown et al. 2005). These authors have also suggested that lower visual field information is processed in the dorsal stream, which is action related, according to Goodale and Milner (1992). Therefore, the use of the lower visual field is also appropriate for controlling lower limb movements.

Four different gaze fixation locations were observed in the present study, although only one was consistently present for each group. Patla (2005) has suggested that these different fixation locations serve specific purposes. Fixations on the obstacle (i.e., area-to-avoid) serve two purposes. First, it provides information about the size/shape of the obstacle. Second, it is used to estimate the relative distance to the target. This relative distance information coupled with normal step length and width information derived from proprioceptive sources can be used to estimate where the foot would land relative to the obstacle if no changes to the stepping patterns were made. Fixations on other areas can be used to estimate how far the foot would have to be displaced from its normal landing spot for each of the four options of stepping long, short, medial, or lateral. These two pieces of information (i.e., normal landing position and amount of foot displacement for each option) are critical, since it has been proposed that minimizing foot displacement is one of the major parameters used when selecting alternate foot placement (Patla et al. 1999; Moraes et al. 2004).

*Alternate foot placements seem to be defined a priori and are independent of obstacle configuration*

The absence of consistent gaze behavior during the approach phase and the high contribution of step N to the adjustment in step N+1 suggest that alternate foot placement was defined *a priori* and gaze data were not systematically used to identify obstacle location and other landing options. For local anchor group for the conditions with one obstacle, most of the fixations on area stepped were quite long ($\geq$ 500 ms). This suggests very little foveal search for other possibilities. Further evidence is provided by the behavioral data. Four of the participants systematically chose the same combination of alternate foot placement, independent of obstacle configuration (lateral/medial for three and lateral/lateral for the other). Therefore, fixations during the approach phase were used to eventually check obstacle location and amount of foot displacement to other options, but alternate foot placement seems to be defined *a priori*.

*Complexity of the task and limited time seem to eliminate travel gaze fixation*

The mechanisms by which the visual system extracts relevant information from the environment for adaptive locomotion has been recently addressed in tasks involving stepping over obstacles, specific foot placement requirements, and steering (Patla and Vickers 1997, 2003; Patla 2004; Hollands et al. 2002). These studies have revealed a common behavior that they call “travel gaze fixation”. This gaze behavior consists of fixating on some point ahead on the travel path and it moves concurrently with the gait speed. They argue that this behavior would provide the information about self-motion necessary to regulate locomotion speed. Fixation on the area ahead presented in the current study is not the same as the travel gaze fixation observed by Patla and Vickers (1997, 2003) and Hollands et al. (2002). In *travel gaze fixation*, the fixation point moves along with the participant. *Fixation on area ahead* is an anchor point and it does not move along with the participant. Interestingly, in the present study, travel gaze fixation was never present. This absence is quite surprising since Patla and Vickers (1997, 2003) and Hollands et al. (2002) have shown that travel gaze fixation dominates in tasks involving stepping over an obstacle in the travel path and in tasks requiring change in locomotion direction. Two aspects may explain the difference. First, in the present study, only the steps near the obstacles were analyzed. Patla and Vickers (1997, 2003) and Hollands et al. (2002) analyzed more steps during the approach phase. Second, task requirements were simpler in the previous studies than they were in the present study. For instance, Patla and Vickers (1997) required participants to step over an obstacle placed several steps ahead them. An additional novel finding of the current study, therefore, seems to be that when task complexity is increased along with a decrease in time to accomplish it, travel gaze fixation behavior does not seem to occur. Further analysis aimed at examining gaze behavior throughout a longer portion of the path is needed to determine if fixation on the area of interest is limited only to the steps closer to the obstacle region or if it appears throughout the task.

*Summary*

In summary, when two obstacles to be avoided were presented in sequence, subjects used the strategy of planning the avoidance movement globally. Interestingly, two groups, based on the gaze fixations in the adaptive step, emerged from the present study. For one, the last fixation was systematically focused on the area stepped upon; and for the other, the last fixation was always at a point ahead of the monitor area. These two groups represent two different strategies that can be used to extract relevant information for the fine-tuning of foot placement. In addition, task complexity and time pressure seemed to eliminate the occurrence of travel gaze fixations.

# Chapter 5

# General discussion

The series of studies presented here are the first to address systematically how adaptations in gait behavior are selected, planned and implemented. Previous work in adaptive locomotion has focused on how we react to unexpected perturbations (Cham and Redfern 2001; Marigold et al. 2003; Oates et al. 2005) or how we proactively control locomotion to avoid or accommodate uneven terrains (Mohagheghi et al. 2004; Patla et al. 1991; Prentice et al. 2004). In the latter case, though, the environment or task specified what the subject should do. However, in the absence of these specifications, the challenge for the control system is increased. In real life we are usually faced with the possibility of choosing what to do in order to avoid an undesirable area. This selection possibility has not been systematically investigated before, as pointed out by Elsinger and Rosenbaum (2003).

Previous work on the selection of alternate foot placement has shown that individuals systematically choose an area to step on according to obstacle size and position relative to the normal landing spot (Patla et al. 1999; Moraes et al. 2004). The choices are not random, then; rather they are very systematic. In addition, these authors have also proposed that three determinants were used when selecting alternate foot placement: minimum foot displacement, stability, and maintenance of forward progression. The present thesis addressed two main purposes: 1) to validate the alternate foot placement determinants originally proposed by Patla et al. (1999), and 2) to test the generality of these determinants when more than one step has to be modified. Three studies were presented in the preceding chapters and they were designed to assess different aspects of the alternate foot placement model (Figure 1).

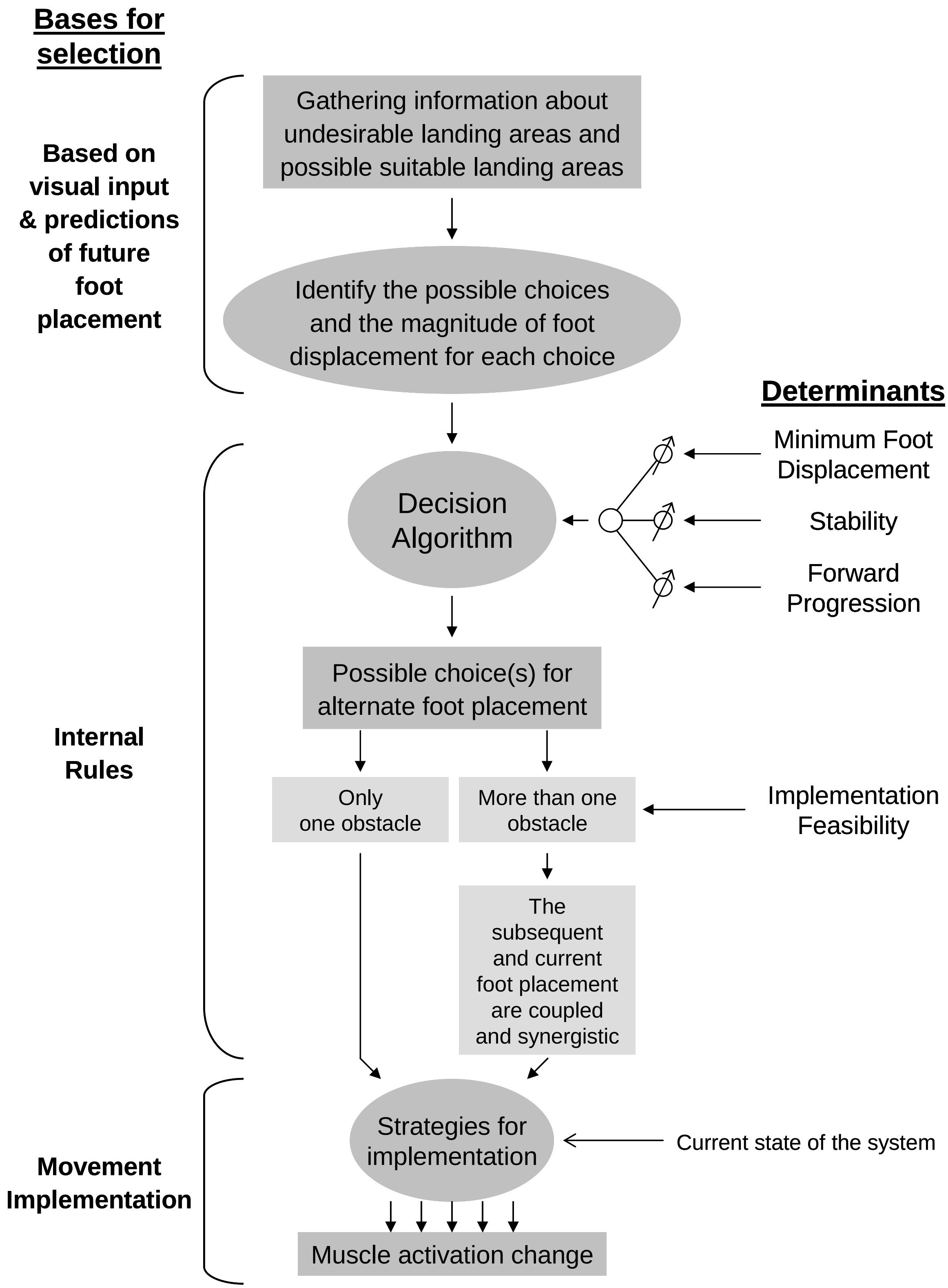


*Figure 1*. Expanded alternate foot placement model showing the bases for selection and the determinants.

The first study (Chapter 2) addressed three issues. First, it validated the virtual planar paradigm through the comparison of real and virtual scenarios. Second, it addressed the validation of the economy determinant in alternate foot placement selection. Third, it addressed alternate foot placement implementation through the analysis of changes in muscle activity. The second study (Chapter 3) addressed the validation of the stability determinant in alternate foot placement selection. It also addressed how the removal of the alternate foot placement selection component would affect movement planning and implementation. The third study (Chapter 4) tested the generality of the three previously described determinants by asking participants to avoid two planar obstacles in sequence. In addition, it addressed the nature of the visual information, which relates to both obstacle size/shape identification and movement implementation.

**Use of a virtual planar obstacle is representative of a real scenario**

The first study described in this thesis validated the use of the virtual planar obstacle paradigm as representative of a real situation. In this case, a real situation was represented by a hole six centimeters deep. The results presented in Chapter 2 clearly showed that behaviorally there was no difference between the conditions using a hole (real condition) and the virtual planar obstacle (virtual condition). The only parameter that seemed to be affected was $T_{COM}$ velocity in the AP direction, possibly for the purpose of allowing the subject to move away from the hole area as fast as possible. It would be interesting to further investigate the reasons for this increase in $T_{COM}$ velocity in future studies, although at this point there is no reasonable formulated hypothesis for this increase.

## Gathering information for selecting and planning alternate foot placement

In the experiments reported in this thesis, the undesirable area was defined by the limits of a virtual planar obstacle displayed in the screen of a LCD monitor. Vision is the only sensory system through which individuals can identify this undesirable area because it can provide information about a bright stimulus at a distance (i.e., exteroceptive information) (Patla 1997). Fixation on the area-to-avoid directs the obstacle to the fovea, increasing obstacle size and shape resolution. In fact, Patla (2005) has shown that when several steps are available for selecting and implementing alternate foot placement, obstacle fixations frequently occurred three steps before the obstacle. Yet, in the study reported here, where gaze behavior was monitored, such consistency in obstacle fixation was not shown. Perhaps time pressure and the use of a default response may explain this absence of obstacle fixation. Since participants had only two steps to plan and implement alternate foot placement for the first obstacle, it is possible that reduced available time reorganized the alternate foot placement search strategy. In addition, since participants used a default response, there was no need for systematic obstacle fixation. The obstacle fixations that eventually emerged might be necessary for the checking of previous estimates of obstacle size and location.

Although there was no consistent fixation on the obstacle, obstacle identification would be necessary in order for the individual to start implementing the necessary changes to achieve the goal of avoiding the obstacle, even if the response was defined *a priori*. In this case, peripheral visual information can be used to provide information about object location (Danckert and Goodale 2001, 2003; Brown et al. 2005) and this information was then used as one of the inputs in the alternate foot placement model.

**Validity of the determinants and their relative task-specific weighting**

The present study has shown that participants systematically exhibits a preference for lateral adjustments over medial adjustments when the minimum foot displacement is satisfied for both options. This finding is particularly striking in the second experiment (Chapter 3), where one of the conditions was similar to the Patla et al. (1999) study. Patla et al. (1999) found that when only one step was available for alternate foot placement, medial adjustments were preferred. We were unable to replicate this finding in the present study. As speculated upon in Chapter 3, this difference might be related to the mechanical apparatus that could provide some cue before the light is turned on. Another issue may be related to stimulus identification (i.e., planar obstacle identification). Schmidt and Lee (2005) have suggested that stimulus intensity, i.e., the brightness of a light stimulus, has an effect on reaction time. In the original work, a mechanical apparatus with lights underneath was used and it created a brighter stimulus than the use of a LCD monitor. Since no difference was found between real and virtual conditions for the dominant choices, the stimulus intensity was appropriate for the present study. However, the overall impact of stimulus intensity needs to be addressed in future studies in order to get a better understanding of this aspect of alternate foot placement.

Patla et al. (1999) and Moraes et al. (2004) have suggested that three determinants are critical for selecting alternate foot placement: minimum foot displacement, stability, and maintenance of forward progression. Moraes et al. (2004) have provided the first quantitative evidence that alternate foot placement is selected to minimize foot displacement, although it is not the main determinant as advocated by Patla et al. (1999). The first study suggests that people try to minimize foot displacement in order to increase economy. It was found that changes in muscle activity were correlated with changes in foot displacement. Also, for almost all obstacles tested in the different experiments, the dominant choice was in the same direction as the predicted minimum foot displacement (PMFD). Not only that, but the actual foot displacement was just slightly bigger than the PMFD, suggesting that during the process of alternate foot placement, the information about foot displacement in all four directions is used and the control system effectively minimizes foot displacement. The fact that minimum foot displacement is used in the decision algorithm suggests that this information needs to be estimated. Patla et al. (1999) and Moraes et al. (2004) have suggested that visual information combined with proprioceptive information is used to estimate what would be the normal landing position of the foot, and then, based on this, foot displacement in any direction is computed. In fact, Patla (2005) has shown that individuals fixate gaze on the obstacle and potential locations for alternate foot placement, and he suggests that these fixations are used to identify normal landing positions in the absence of an obstacle and the amount of foot displacement for each option (i.e., long, short, lateral, and medial). A mechanism by which this visual and proprioceptive information could be integrated in order to estimate future foot placement is the forward internal model (Wolpert et al. 1995; Witney et al. 2001). The outputs of such a forward internal model could be used for the selection of alternate foot placement that minimizes foot displacement.

The three determinants above are ordered relative to the task, and precedence occurs by defining the determinant that is the first, second and third priorities. Eventually, two determinants may have the same contribution and therefore they are weighted equally. This idea of defining a set of priorities is not completely new. In fact, Rosenbaum et al. (2001a, 2001b) have proposed a prioritized list of requirements or what they called a constraint hierarchy, which is used to select the goal-end posture in upper limb movements. In other words, the constraint hierarchy defines the task functionally by identifying what the priorities are when performing it. For instance, in the case of reaching for the off switch of a rotating electric saw, it is most important not to collide with the saw, it is less important to reach the switch, and it least important to move with little effort (Rosenbaum et al. 2001b). The idea of a constraint hierarchy is also important because it assumes multiple constraints rather than one, as in previous prevailing ideas in motor control research (Uno et al. 1989). Although the constraint hierarchy was originally conceptualized for the planning of a movement with a specified goal, this idea may also be adapted to alternate foot placement selection. In fact, Bahrami and Patla (2005) have modeled alternate foot placement selection based on these three determinants by properly weighting them according to task priorities, like those used in the constraint hierarchy. By using this model, they were able to correctly predict 80% of the choices.

The studies of Patla et al. (1999) and Moraes et al. (2004) suggest that the number of steps available for implementing alternate foot placement affects the determinants' priorities. When only one step was available for implementing alternate foot placement, priorities were satisfied in the following sequence: minimum foot displacement, stability, and maintenance of forward progression. However, when more than one step was available, maintenance of forward progression was the most important determinant, followed by stability and minimum foot displacement. The results of the experiments reported here provide additional combinations for the determinants' priorities in different contexts. The results of the second experiment show that under time pressure (i.e. one step) and similar foot displacement for the same plane, stability is the first priority, followed by minimum foot displacement and maintenance of forward progression. In fact, all three experiments showed that when the foot displacement is the same for options in the same plane, lateral and long choices are preferred. The results of the second experiment show clearly that this preference is stability based. Therefore, when similar foot displacements are found for more than one option in the same plane of motion, stability is the main determinant guiding alternate foot placement selection.

Predictability of potential instabilities associated with some choices may be obtained by forward internal models and the control system uses this information to make either a long or lateral adjustment when similar foot displacement could be achieved in the same plane of motion. Winter (1995) has shown that the posture control system can anticipate instabilities generated by the movements as observed in the low variability present for the support moment and the high variability present in the individual hip and knee moments of force. This high variability is the result of a trade-off between hip and knee for trunk control and support against gravity (Winter 1987). Therefore, predictive information about foot displacement and stability are used in the alternate foot placement selection stage in order to choose the response that is more appropriate to the specific obstacle size and location.

In addition, the third experiment showed that the presence of a second obstacle had an impact in the determinants' priorities for the first obstacle. When minimum foot displacement was present in the frontal plane for more than one option, stability was the first priority, followed by minimum foot displacement and maintenance of forward progression. However, when the minimum foot displacement was present for options in the sagittal plane, the first priority was none of the previous determinants, but rather a new one, facilitation of the subsequent alternate foot placement. This determinant was followed by stability, minimum foot displacement and maintenance of forward progression. For the second obstacle, the strategy used seems to be different, depending on the individual. The only consistent strategy was observed for three participants. They seemed to select the choice for the second obstacle according to the following determinants sequence: 1) avoid the crowded area and 2) stability. Maintenance of forward progression and minimum foot displacement seem to have almost no contribution for the choice for the second obstacle. Therefore, the priorities in each of these contexts are slightly different and even new determinants seem to emerge with task complexity. These findings have an important impact for modeling purposes and also applications in robotics, particularly in making robots more adaptable to cluttered terrains by allowing them to search for and select the options that satisfy these determinants. Theoretically, these findings indicate that it is important to look at multiple parameters when studying movement selection and planning.

**Alternate foot placement implementation**

The goal of movement implementation is to transform the selected response into neural commands to the effector system. One point of interest is the decreased stability associated with the removal of alternate foot placement selection. It was proposed that externally-triggered alternate foot placement affects postural control modulation since it could diminish the overall activation of the brain areas involved with locomotion control. Movement implementation was studied at a neurophysiological level by looking at changes in muscle activity. Several muscles of both limbs and trunk were monitored while performing the alternate foot placement task. Changes were phase and muscle specific, although they varied between real and virtual conditions. Drew et al. (1996, 2004) have suggested that the descending command from the motor cortex appears to functionally interact with the central pattern generator (CPG) to adapt basic locomotion. Moreover, this cortical motor command was found to control specific components of gait by influencing the activity of a single muscle or a small group of muscles acting around a single joint (Drew et al. 1996). However, the control system seems also to have some flexibility in terms of implementing the changes to achieve a goal. It is well established in biomechanical textbooks that different combinations of force generations in agonist and antagonist muscles may result in the same net moment of force and, consequently, in the same movement. The concept of motor equivalence (Abbs and Cole 1987) may be helpful for understanding the use of different combinations to achieve the same goal, although it does not explain why individuals performed differently in the real and virtual conditions. Motor equivalence represents the use of variable means to achieve an invariant end. The differences observed here between real and virtual conditions stress the fact that different muscle combinations or synergies may be used in order to achieve the same goal and its use may be related to the current state of the system. It seems that there is no unique way to implement a movement in order to achieve a goal. Although while at the muscle level the implementation may be slightly different, the behavioral result seems to be unaffected.

**Final guidance of foot to avoid the obstacle**

Visual information was shown to be used online for controlling alternate foot placement. However, two different strategies emerged from the gaze study. First, half of the participants fixated on the area stepped upon until almost the point of heel contact for alternate foot placement. Second, the other half of the participants anchored their gaze on an area ahead of the monitor and they were assumed to use the lower visual field for controlling alternate foot placement. This finding is interesting because it reveals the nature of the strategies used and clearly shows that people use visual information differently. The reasons for these differences are unknown and future studies should be designed to address this issue more systematically.

## Conclusions

The three studies presented here allowed us to validate the three determinants used by the control system to select alternate foot placement when avoiding stepping on an undesirable location. Individuals tried to minimize foot displacement for the sake of economy as well as choosing the option that was more stable, and they attempted to minimize deviations from the end-point goal (i.e., maintenance of forward progression). In addition, the presence of a second obstacle showed that choices for the first one were related to these determinants, but the choices for the second obstacle were not. Therefore, the determinants are quite appropriate to model the choices when only one obstacle is present in the pathway. However, studies involving more obstacles with different configurations are needed to expand the determinants used in those cases. Therefore, the generality of the determinants seems to be restricted to one obstacle in the travel path.

## Future studies

Although the present findings validated and expanded the alternate foot displacement determinants, the generality of these determinants may be further investigated by looking at different walking speeds and carrying loads. Additionally, the use of an extensive travel path with several obstacles in sequence can provide better understanding of the global and local planning mechanisms. Also, the use of odd shapes, which are more similar to daily life obstacles, should be investigated to further validate the alternate foot placement determinants.

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