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An exploratory analysis of the effect of target geometry on kinematic variability during adaptive locomotion

by

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Abstract

Bipedal locomotion over uneven terrain is a critical movement skill; however, a paucity of knowledge exists regarding the processes underlying the selection and execution of foot placements. The purpose of this study was to investigate the relationship between geometric features of the walking surface and spatial patterns of movement variability. Twelve healthy young adults completed a series of blocked trials in which they walked at a self selected pace, using two interchangeable blocks as footholds. The shape and configuration of the stepping blocks was manipulated to create 6 conditions. Foot kinematics were recorded using 3D optical motion capture. Patterns of end–point variability were reflective of stepping block geometry, indicating the movement potential afforded by a surface plays a role in stabilizing the movement pattern. This was interpreted as evidence of a rough terrain strategy which maximizes the probability of successful foot placement and minimizes the need for controller intervention.

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Chapter I. Introduction

Human Locomotion in an Evolutionary Context

Locomotion is a ubiquitous feature of animal life that has evolved through multiple independent lineages into a diverse set of behaviours. This important evolutionary adaptation affords an organism a greater capacity to procure food, encounter mates, and evade threats. Humans exhibit remarkable flexibility and diversity of locomotion and can successfully adapt their locomotory patterns to a variety of physical, social, and pathological constraints. People may shuffle on slippery surfaces, skip when playing a game, dance to convey emotion, or limp when injured. Nevertheless, human locomotion typically refers to the bipedal gait patterns of walking and running. Empirical findings within the field of paleoanthropology suggest that bipedalism first emerged in early hominids approximately 6 million years ago in *Sahelanthropus* as an occasional behaviour subsidiary to quadrupedal arboreal brachiation. Various competing, but not necessarily mutually exclusive, hypotheses account for the selective pressures which subsequently promoted a shift towards almost exclusively bipedal locomotion in *Homo erectus* approximately 1.9 million years ago (Arsuaga & Martinez, 2005; Delson et al., 2000; Stringer & Andrews, 2005). This evolution away from quadrupedal arboreal brachiation was concomitant with the upper limb structures becoming increasingly dextrous and less suited to weight bearing (Gebo, 1996). Given such a phylogenic history, there is reason to expect a conservation of control mechanisms between upper and lower limbs.

Georgopoulos and Grillner (1989) contend that in terrestrial mammals, the neural mechanisms for fine manipulatory ability are similar to, and evolved from, those used to make accurate limb placements during locomotion. Parallels between upper and lower limb movements have also been drawn in empirical studies of motor behaviour (see Glover & Dixon, 2004; Patla & Goodale, 1996; Rietdyk & Patla, 1994). The study of adaptive locomotion can therefore be viewed as parallel to the study of goal directed arm movements with special consideration given to the unique demands of locomotion.

Requirements for Locomotion

Animal movement always occurs within an environmental context. Specific attributes of the environment act as constraints on the behaviour of individuals interacting with it. Similarly, the task being performed also creates unique demands. An individual must generate movements specific to both the task and environmental demands. As such, motor behaviours like locomotion are best understood as a dynamic interaction between task, individual, and environment (see Shumway-Cook & Woollacott, 2001).

According to Patla (1991b), efficacious locomotion requires generation of active propulsion, maintenance of dynamic equilibrium, and provision for adaptation to variable tasks and environments. The implication for bipedal walking is that each step must provide a foot–to–surface interaction with sufficient mechanical properties so as to afford the individual the capacity for subsequent steps.

Secondary factors influencing locomotor behaviour include the minimization of both energy expenditure and stress on tissues. These secondary criteria are robust to violation in the short term but are necessary for the long term functioning of the system (Patla, 1991b).

The criteria of generating active propulsion and maintaining dynamic stability are common to all forms of locomotion and consequently the majority of study has been directed towards characterizing linear, unobstructed gait over level ground. These studies have generated a great deal of descriptive information regarding kinematics, kinetics, and muscle activity, especially in the sagittal plane, during walking and running gaits (see Winter, 1987). The resulting characterization of 'typical' gait patterns has the greatest external validity in the context of modern engineered walking surfaces which are intentionally constructed to be flat and featureless. Such surfaces do not place constraints on where the feet may land.

In contrast, the majority of human evolution has occurred in natural environments with irregular walking surfaces that constrain where the feet may land to a greater extent. In an uneven or cluttered environment, an individual must make purposeful modifications of typical gait patterns to clear obstacles and place the feet on safe footholds. This process was recently described as the rough–terrain problem by Warren (2007). The resulting spectrum of locomotor behaviours implemented when traversing rough terrain are collectively termed adaptive locomotion. The possible changes are numerous but can be generally classified as either avoidance or accommodation strategies (Patla, 1991b).

The generation of the basic locomotor pattern and maintenance of dynamic stability are logically antecedent to their modification for adaptive locomotion. These processes will be discussed in the following sections before exploring avoidance and accommodation strategies further.

Forward Progression and Basic Locomotor Rhythm

A fundamental characteristic of locomotor behaviours is stereotyped rhythmic muscular contractions. This is particularly notable in alternating flexor–extensor activity in the weight supporting limbs. As the ability to move across terrain is ultimately dependent on the generation and application of appropriate force through the legs to the support surface, the relative timing and amplitude of muscle activity is crucial for effective locomotion.

Over the course of the last century, it has become clear that the basic alternating flexor-extensor activation patterns required for locomotion are generated by neural circuits in the spinal cord (Pearson & Gordon, 2000). These circuits are commonly referred to as central pattern generators and abbreviated to CPG. The anatomy of specific central pattern generators has been worked out in several invertebrates and some lower vertebrates. In quadrupeds there appears to be a hierarchy of pattern generators with circuits for each joint influenced by circuits for each limb which are in turn under the influence of a more centralized circuit (Cohen et al., 1988). The mechanisms of CPG function remain however, poorly understood. Even after the structure of its neural circuitry has been worked out, it is extremely difficult to predict the activity of a CPG (Kelso, 1995). The mechanisms elucidated thus far have indeed been so diverse that the term motor pattern network has been proposed to more accurately reflect the phenomena (Harris–Warwick & Johnson, 1989).

It is nevertheless clear that while rhythmic pattern generation at the spinal level is necessary, it alone is not sufficient for normal locomotion (Pang & Yang, 2001; Thelen et al., 1987; Forssberg, 1985). Descending input from the brain is required to initiate the pattern generating circuits and adjust movement patterns (Georgopoulos & Grillner, 1989). The parapyramidal region (PPR) and mesencephalic locomotor region (MLR) are located in the brainstem and have been identified as the source of descending signals that initiate locomotion in mammals (Jordan et al., 2008). These groups of neurons project into the spinal cord and provide tonic signals which regulate the activity of CPGs.

Peripheral sensory feedback is also necessary for successful locomotion. Beer and colleagues (2009) have conducted a series of studies in which virtual legged model agents were evolved computationally. This technique simulates natural selection in order to gain insight into why certain features appear in biology. Three classes of legged models were studied: those with no descending input from a central controller were termed reflexive pattern generators (RPG), those with no sensory feedback were called central pattern generators (CPG), and those with both descending input and sensory feedback were called mixed pattern generators (MPG). The most successful strategy was the mixed pattern generator because it could use sensory information to adapt to its environment; however if the feedback were lost due to injury or some other reason, it was still capable of a degree of functioning. Findings such as these begin to demonstrate the necessity of flexible movement patterns.

Dynamic Stability

During bipedal locomotion, the majority of the step cycle is spent with only one leg in contact with the ground. During this time, the centre of mass of the body is outside of the base of support provided by the foot in contact with the ground and the system is not in a state of static stability. This type of mechanical stability is however only a special case of stability, which can be more broadly defined as "the capacity of a system to return to a given state after a perturbation has driven the system away from that state" (Scholz & Schoner, 1999). Maintenance of dynamic, rather than static, mechanical stability is thus essential for successful locomotion and is dependent on a continuous process of repositioning the base of support.

Several authors have described walking as a cyclical process of falling forward and re–establishing balance by moving the centre of pressure ahead of the body with a new foot placement (Redfern & Schumann, 1994; Winter, 1995; Patla, 2003). Another perspective is held by Lyon and Day (1995, 2005) who contend that balance is maintained during walking through a predictive throw of the centre of mass of the body that is coupled to intended foot placement. Irrespective of theoretical stance, the maintenance of dynamic stability is accomplished with three distinct subsystems: reactive, predictive, and proactive control (Patla, 2004).

Reactive control involves both monosynaptic and polysynaptic reflexes that facilitate short latency corrective responses to unexpected perturbations. The response elicited by these reflexes is specific to both task and phase of the movement. They can be modulated via changes in gain and in some cases sign reversal (Dietz, 1992; Stein, 1991). In a study conducted by Nashner and colleagues (1979), electrical stimulation of cutaneous receptors elicited different responses depending on whether the leg was traveling up or down. These results are indicative that the nervous system adapts reflexes in a context dependent fashion. This phenomenon has come to be known as the phase dependent modulation of reflexes and allows for the simultaneous provision of stability and adaptability during locomotion without relying on slower cognitive responses (Duysens et al.,1990; Forssberg et al., 1975).

Predictive control involves feed–forward compensatory muscle activity that acts to stabilize expected perturbations generated as byproducts of intended movements. For example, Belenkii and colleagues (1967) measured muscle activity during walking and found that postural muscles were recruited to stabilize the torso just prior to the primary agonists of the thigh and leg.

Proactive control of dynamic stability constitutes actions taken to avoid or minimize perturbations. This type of control requires information about the static and dynamic features of the environment in advance and is facilitated primarily by vision (Dusenbery, 1992). Gait adaptations such as adjustment of step length, width, and height can be frequently be implemented within a single step cycle. However, changes in direction require more time and must be initiated at least a step cycle in advance (Patla, 1997).

Some evidence indicates proactive control is not always utilized and in some circumstances is possibly even counter productive. In a study using guinea fowl, Daley and colleagues perturbed the gait of running birds with a shallow hole in the floor. Mechanical modelling of the responses indicate that guinea fowl maintain dynamic stability whilst running by employing intrinsic mechanical properties of their bodies rather than extrinsic motor control. In fact, the birds navigated the hole in the floor much more successfully when they could not see it compared to when it was visible (Daley et al., 2006). These results support McGeer's predictions that a passively walking robot could maintain stability after mild perturbations (McGeer, 1993).

Nevertheless, these results have not been replicated in humans and it is likely that proactive, predictive, and reactive mechanisms function in concert to effect the maintenance of dynamic stability. The resulting behavioural modifications brought about by these mechanisms can be described as either accommodation or avoidance strategies.

Accommodation and Avoidance Strategies

Accommodation strategies are employed when the surface is different but not necessarily hazardous or inadequate. Surfaces that need to be accommodated include those with different slopes like a hill or a ramp, different geometry like stairs or a curb, different compliance like sand or soggy turf, and different friction properties like ice. Implementing accommodation strategies usually involves modification of specific features of gait patterns over several steps. Although more encompassing changes may occur as in avoidance strategies, these changes are secondary.

More research has been directed to avoidance strategies which usually involve the modulation of ‘global’ parameters of the step cycle and are employed to avoid stepping on a surface perceived to be inadequate or unsafe. Modifications can include step length and width, ground clearance height, direction of travel, and stopping. These adjustments are global in the sense that a large portion of the locomotor apparatus is involved; however they usually take place in a discrete period over one or two step cycles.

Alternate Foot Placements

The implementation of avoidance strategies frequently requires intentional movement to an alternate foot placement in order to avoid a surface perceived to be unsafe. The process by which these foot placements are selected has been shown to be systematic and non random (Patla et al., 1999). A set of internal rules seem to guide the selection of foot placements based on a semi flexible hierarchy of criteria. Provided that a candidate surface region does not compromise the safety of the individual, priority is given to the placement requiring minimal displacement of the foot. This judgment is based on exteroceptive information made relative to the spot where to the foot is predicted to land without intervention. When multiple areas satisfy this criterion equally, the locomotor system tends to ensure mechanical stability by lengthening and widening the step rather than stepping short and medial of the original footfall position. A preference for movements in the direction of travel as opposed to in the frontal plane has also been observed (Moraes et al., 2004; Moraes & Patla, 2006; Moraes et al., 2007). These findings are consistent with the three essential requirements for successful locomotion outlined previously (Patla, 1991b).

In whole, the body of experimental evidence generated by Patla, Moraes, and colleagues substantiates the hypothesis that gait modification parameters and specifically the selection of alternate foot placements are made systematically. The system prioritizes the safety and integrity of the individual before the capacity for forward progression. Similarly the immediate need for forward progression dominates the need for long term energy efficiency and force minimization. See Moraes et al. (2007) for details on the development and validation of an algorithm for foot placement selection.

While the selection of a single alternate foot placement is essential, it is clear that ecological constraints require multiple such adaptations. As Rietdyk and Drifmeyer (2010) have pointed out, landing on a single safe ‘foothold’ is a simple case of the more general rough terrain problem described by Warren (2007).

Investigations into the rough terrain problem can be generally classed into two experimental paradigms: locomotor pointing or obstacle avoidance. The related terms locomotor pointing and locomotor targeting have been used inconsistently in the literature. While locomotor targeting refers to a task in which the entire foot must be placed within the bounds of a visually specified target area, locomotor pointing involves the placement of the toes to a line or point. Much of the literature has thus far made an implicit assumption that the same mechanisms underly action in both pointing and targeting tasks. Evidence in support of this comes from a targeting study conducted by Bradshaw and Sparrow (2002) in which target size was manipulated. They observed that the toe was consistently placed near the anterior boundary of the target with no significant differences as a result of target size. Although not directly tested, one can extrapolate the target size reduced to a line and expect similar foot placement patterns.

Another important distinction is made between hard and soft impacts. In a hard targeting impact, the individual continues motion past the target as is the case in most athletic events. Less research has been conducted regarding soft impacts where the individual comes to a stop within the target area (see Kim et al., 1993). Bradshaw and Sparrow (2002) provide the example of targeting and stopping at the edge of a curb before crossing a road as the most common case of soft targeting.

Locomotor Pointing

Early locomotor pointing studies examined the approach phase of long jumpers as they ran up to and targeted the take–off board. Through observation of footfall position variability, Lee et al. (1982) and Hay (1988) characterized a two–phase gait regulation pattern. In the first accelerative phase, small step to step differences accumulated resulting in increasing footfall positional variability as a function of step number. This trend reversed approximately four steps prior to the take–off board when footfall position variability decreased sharply to precise placement on the take–off board. These findings have been interpreted as evidence for a two–phase regulation system or strategy where the initial accumulation of variability reflected an unregulated phase that switched to a visually regulated step adjustment phase in the last few strides. The peak of footfall variability thus corresponds to the point at which the system switched to visual regulation. This two–phase regulation has been replicated in several studies and appears to be a robust pattern across both proficiency levels and athletic events (Berg et al., 1994; Bradshaw, 2004; Maraj, 2002; Renshaw & Davids, 2006).

Montagne and colleagues (2000) observed similar patterns of footfall variability but conducted a unique step–by–step correlation analysis. They concluded that instead of a two phase regulation, individuals used a continuous perception–action coupling. This proposed mechanism makes step length adjustments based on need; an error is detected only after a threshold of accumulated error is attained. The two–phase pattern develops because proximity to a reference point such as the target is required in order to detect the accumulated error.

Bradshaw and Sparrow (2002) noted an inverse linear relation between movement time of the approach phase and length of the target. This was consistent with the hypothesis that the approach will be slowed to facilitate the more accurate movement needed to target a smaller spatial constraint.

When compared to pointing tasks performed whilst running, it is expected that pointing during walking will utilize the same basic mechanisms and display a similar pattern of footfall variability that is scaled down with adjustments occurring primarily over the last step. Bradshaw and Sparrow (2001) conducted a pointing study in which subjects walked, jogged, and sprinted toward the target. Their results confirmed a similar kinematic profile exists across approach speed and demonstrated that accuracy of final foot placement and approach velocity observe an inverse linear relationship. While there is not yet consensus regarding the underlying principle that determines when visual regulation of gait is initiated, it is clear that the largest adjustments are made closest to the targets.

Obstacle Avoidance

The second aspect of the rough terrain problem is generally concerned with adjustments of limb trajectory over obstacles in the travel path. Although prospective visual information about the environment permits route–planning which avoids obstacles entirely, the adjustment of limb trajectory over or around obstacles that that remain in the travel path has been the focus of most studies.

Santos, Moraes and Patla (2010) conducted an obstacle avoidance study in which the size of the obstacle was manipulated dynamically during each trial. They observed that regardless of the magnitude of the size change, the lead limb exhibited a default limb elevation. The trailing limb did, however, adapt toe clearance height proportionate to obstacle height.

Evidence for the use of online visual control during obstacle avoidance comes from studies in which the lower portion of the visual field was obstructed as participants stepped over obstacles. The findings of von Hedel et al. (2002) demonstrated that the initial response to obstruction of the lower visual field is an exaggerated margin of toe clearance. With repetition, the clearance margin decreased. When compared to conditions of full visual availability, obstruction of the lower visual field results in greater toe clearance and increased distance between foot placement and the obstacle (Patla, 1998; Mohaghaghi et al., 2004). These findings indicate the visual system functions in an online fashion and acts to increase the efficiency of obstacle clearance by reducing the safety margin and allowing the foot to pass closer to the obstacle.

In a hybrid targeting–avoidance experiment conducted by Moraes, Allard and Patla (2007), participants were required to make adaptive movements to avoid a planar rectangular obstacle that was lighted one step prior to impact. Movements were made under either free choice or forced selection conditions. The alternate foot placements freely selected by participants strongly tended to be long and lateral, lengthening and widening the step respectively. It is presumed that this strategy was employed because it increases stability. During the forced selection trials in which participants were instructed where to place the foot relative to the obstacle, individuals were successfully able to avoid the obstacle and remain stable. This was true even when the foot placement was short and medial to the obstacle. These findings demonstrate both the use of online visual control as well as the flexibility and robustness of the system. Converging evidence increasingly indicates that the locomotor system will prioritize safety of movement by adopting a default strategy with the highest likelihood of continued locomotion. See also Perry et al. (2001) and Patla et al. (1991).

Foot Reaching

Another line of research has made efforts to parallel existing reaching literature as closely as possible. In an effort to reduce the number of variables present during actual locomotion, several authors have conducted investigations into single foot 'reaching' to a target from a standing position (Glover & Dixon, 2004; McCarville & Westwood, 2006; Reynolds & Day, 2005a).

Reynolds and Day (2005a) conducted a related experiment in which participants were required to adjust to a planar lighted rectangular target that moved mid–swing rather than avoid the area as in the study by Moraes, Allard and Patla (2007). Again, individuals were able to make appropriate online adjustments and step within the bounds of the target. In comparison to a 'reach' condition, in which balance constraints were removed via the use of handrails, foot movements were larger in magnitude than in a typical stepping condition without handrails. The authors interpreted an absence of differences in response latency or movement time as evidence for the existence of a short latency visuomotor pathway for the leg similar to that of the arm. The results also demonstrate that swing trajectory and thus foot placement can be altered to at least some extent mid–swing without compromising balance. Congruent with what would be predicted based on upper limb reaching literature, all three of these studies concluded that online visual control was used.

A component of the rough terrain problem for which there exists a relative lack of experimentation and knowledge is the ‘stepping stone’ paradigm. This situation can be thought of as an extension of the reaching experiments and the inverse of obstacle avoidance. Stepping stones, or more generally discrete geometric objects, represent safe footholds over a hazardous background whereas traditional obstacle avoidance has geometric objects as discrete hazardous areas over a safe background.

The Role of Vision

Vision provides the majority of information necessary to adapt gait patterns because it acts at a distance thus allowing anticipatory rather than reactive adjustments to be made. The contribution of visual perception to the control of locomotion can be subdivided into the relevant information extracted from the environment and sampling characteristics that determine how the information is obtained. Surface characteristics including friction, compliance, and geometry influence visual perception as well as modulation of gait. Similarly, obstacle characteristics including geometry, material, colour, number, layout, and whether they are static or dynamic ultimately influence visually mediated gait modulation. Other influencing factors include lighting conditions, subject characteristics, and task features. The last category includes task goal, consequences of error, and form of locomotion (Patla, 1991b).

The classical perspective on visual processing maintains that there are key environmental features within the visual field which must be extracted and processed in the central nervous system. In this view, meaning must be imparted upon the salient features. On the contrary, theories of ecological psychology posit that relevant information is directly perceived, without processing, from the optical flow field (Gibson, 1958, 1979). From this perspective, control is not imparted upon the system by the brain, but is an intrinsic attribute of the animal–environment system.

Adaptive locomotion is highly reliant upon both exteroceptive and exproprioceptive information. Vision provides prospective information about the environment; this is termed exteroceptive information and informs the individual about desirable and undesirable landing spots in the travel path. Exteroceptive information is used in feedforward control of walking over obstacles (Mohagheghi et al., 2004; Patla & Vickers, 1997; Patla, 1997, 1998). When vision is coupled with proprioception, the relative displacement of body segments, including the foot, is also known (Moraes, Allard & Patla, 2007). This relation between the target and the individual is termed exproprioceptive information (Rietdyk & Drifmeyer, 2010).

Hollands et al. (1995) demonstrated that when each step is constrained to a target area, gaze is directed towards foot–fall for each step. This is in contrast to gaze being directed some distance ahead during unconstrained walking. Lyon and Day

(1995, 2005) established that future foot placement is coupled to body motion and is pre–planned before foot–off. It has also been shown that when vision is occluded during swing phase, the resultant intermittent visual availability is sufficient for goal directed stepping (Hollands & Marple–Horvat, 1996; Patla et al., 1996a).

It is also possible to use vision to adjust the trajectory of a leg during swing phase. During unconstrained walking, swing durations are typically between 400 and 450 ms (Blanc et al., 1999; Mills & Barrett, 2001). These values are in excess of the minimum 120 ms necessary to respond to a visually detected perturbation (Reynolds & Day, 2005b). While online foot trajectory corrections can be made, this may not be the typical mode of visual coupling during locomotion (Reynolds & Day, 2005a, 2005b). Successful locomotion is possible without precise online control during each step. This is consistent with current understanding of human evolution as there would have been strong selective pressure to free vision from the ground when walking in order to navigate, detect predators or other danger, and track animals whilst hunting (see Patla, 2004).

In sum, a substantial body of evidence regarding the role of vision during locomotion permits several conclusions. Vision provides the majority of information needed to navigate and negotiate rough terrain. Because it acts at a distance, visual information permits anticipatory movements thus freeing the system from the need for continuous visual sampling of the terrain. Intermittent visual sampling is adequate for both unconstrained and adaptive locomotion (Thomson, 1983; Assaiante et al., 1989; Patla et al., 1996a). Such prospective perception–action coupling appears to be the preferred mode during adaptive locomotion. If necessary, vision can be used in a continuous online fashion to facilitate mid–swing trajectory adjustments when accuracy requirements are increased or when surface characteristics are dynamic. Lastly, a speed–accuracy tradeoff is at play both at the level of leg swing (Reynolds & Day, 2005b) and at the level of approach velocity (Bradshaw & Sparrow, 2001).

Execution of Adaptive Movements

During unconstrained locomotion, the duration of stance phase is highly covariant with respect to the period of the gait cycle (Herman et al., 1976; Shapiro et al., 1981). The duration of stance phase is thus also inversely related to walking speed. In contrast, a consistency observed in the gait patterns of many species is a relatively invariant duration of swing phase throughout a range of walking speeds (Rosenbaum, 1991). Unlike stance phase, where the foot is constrained by its contact with the ground, the leg is free to vary in its trajectory during swing. Biomechanical analyses reveal the hip flexors provide a relatively speed independent impulse and pull the leg forward in a ballistic fashion, essentially setting it into projectile motion (McMahon, 1984).

The primary means of implementing an avoidance strategy is modulation of step length and width over several strides preceding the obstacle or target. Step length is modulated by changing the vertical impulse applied by the contralateral leg during stance (Lee, Lishman & Thomson, 1982; Berg, Wade & Greer, 1994). This allows more or less time for swing following the ballistic swing impulse effectively altering the height at which the limb is launched into a projectile trajectory.

An important consideration is that the division of the body into systems is somewhat of an artificial one. While the nervous system functions as a controller, it does so as part of the body. It contributes to the mechanical properties of the system under its influence. Conversely, the musculoskeletal system is not just a puppet of the nervous system, it can play a central role in the control of movement. The ballistic leg swing strategy requires very little neural control of the movement, relying instead upon the mechanical response of the limb within a gravitational field to create a movement plan. These mechanisms have been evaluated almost exclusively in either unconstrained or single target paradigms. However, as noted by Rietdyk and Drifmeyer (2010), the rough terrain problem includes multiple instances of sequential targeting and obstacle avoidance. The mechanisms of limb trajectory adjustment may be significantly more complex than straightforward impulse modulation. The mechanical properties of the body segments may still contribute to control in a constructive way rather than just passively be controlled. A paucity of knowledge exists regarding the nature of such modulations but it stands to reason that they would be highly dependent on the specific foot placements which are in turn determined by environmental characteristics.

An upper limit to the degree to which step length and width can be modulated, and thus a boundary on relevant environmental features, is set by anatomical properties specific to the individual. The most significant of these is leg length which sets a theoretical maximum step length as the joint angles of the hip increase and the legs approach an angle parallel to the surface. In practice this theoretical maximum is much larger than the longest step length functionally available to most individuals. Passive joint structures, particularly at the hip, generate increasing levels of resistive torque as joint angles increase (Davy & Audu, 1987). Furthermore, the force generating capacity of the overlying associated muscles is finite and the force required for drastically increased step lengths scales non–linearly (Alexander, 1989). The combined effect of body mass, leg length, passive joint properties, and active muscular properties interact in a complex manner both at short time scales, determining absolute ranges of motion, and at longer time scales, determining what range of motion is sufficiently efficient to satisfy evolutionary constraints on the energetic cost of locomotion (Inman et al., 1981; Jungers, 1982; Willems et al., 1995). Internal neuromechanical factors thus define both absolute and practicable workspaces within the environment that are accessible to the individual.

Irrespective of the mechanisms driving the movement, the selection of an alternate foot placement within the accessible workspace appears to be based on a hierarchy of criteria. The system favours movements requiring the least displacement and thus the least energy. If alternatives of equal displacement are available, priority is given to adaptive movements in the plane of progression as opposed to lateral adjustments as this facilitates the goal of forward progression (Patla et al. 1999). Stepping longer instead of shorter creates a larger base of support that enhances stability; however, it is not yet entirely clear what determines whether medial or lateral movements are favoured (Patla et al., 1999; Moraes et al., 2004). Despite its logical organization, it appears that in many instances, this hierarchy is at least partially violated without compromising locomotor efficacy. This raises important questions about the definition of error and the interpretation of variability in movements.

Noise and Variability

The development of information theory in the mid twentieth century by Shannon & Weaver (1949) laid the groundwork for many foundational theories of information processing in sensorimotor behaviour. Central to many of these studies was an assumption that variability of motor performance was the direct result of noise in the system (Newell et al., 2006). For example, speed–accuracy tradeoffs have been observed both in approach velocity during jumping events and during more constrained foot reaching studies. The classic speed–accuracy tradeoff developed formally by Paul Fitts held that the sensorimotor information channels had a maximum bandwidth. Background noise would add to the signal, occupying bandwidth and leaving less bandwidth available for the true information. This situation prevents a portion of the original data from reaching its destination in a given amount of time, thus decreasing output accuracy. The alternative which maintains accuracy with reduced bandwidth involves slowing the movement. This increases the time available for all the data to arrive and the accuracy of the signal, and thus the movement, is preserved (see Schmidt & Lee, 2005 for a comprehensive discussion of speed–accuracy tradeoffs).

Newell and colleagues (2006) make a strong argument that the interpretation of movement variability as a product of noise in the system is an erroneous assumption. Newell and Slifkin reported in a review paper that one of the few common features of variability in motor output is that intra–individual variability does not exhibit the structure of white Gaussian noise and tends to hold time–dependent structure (see Newell & Slifkin, 1998; Riley & Turvey, 2002). It has subsequently been argued that the observation of multiple timescales of variability can be attributed to multiple control structures predicted by nonlinear dynamics.

Reduced outcome variability has long been interpreted as an indicator of increased skill. However, this needs to be viewed in the context of task requirements. Arutyunyan, Gurfinkel, and Mirskii (1968, 1969) studied pistol shooting and observed that movement variability was actually due to compensatory arm movements that acted to stabilize the movement outcome accuracy. This demonstrates the need to conscientiously interpret movement variability relative to task goals because unlike traditional information processing theory, variability from a dynamic systems perspective is a necessary and central part of normal functioning.

As noted, it has become common, if not necessary, to ground the study of movement variability in complex systems theory. Pioneering work by Bernstein (1967) described how successful movement outcomes could be repeated without repeating the movement itself. Bernstein's observation of 'repetition without repetition' laid the groundwork for research examining the degrees of freedom problem. Classic control theory arbitrarily divides multi-joint movements into problems of planning and control (Scholz, Schoner, & Latash, 2000). The degrees of freedom problem is a problem of understanding what variables are specified as part of the plan.

Degrees of Freedom

In adaptive locomotion, as in any motor task, there are more neuromechanical elements contributing to performance than are absolutely necessary. Within the entire human body, this includes the temporal activation patterns of billions of neurons, the force generated in nearly 800 different muscles, and the position of the more than 100 joints (Kelso, 1982). Each of these elements may vary within its respective domain and each is considered to be an independent degree of freedom.

In three dimensional space, an object such as the foot has both an angular and a linear position on each of the three orthogonal axes. Positioning the foot on an appropriate surface area thus requires the specification of six kinematic variables. There are however more than six kinematic degrees of freedom provided by the joints linking the foot in question to the foot in contact with the ground. Mathematically this creates an indeterminate system and does not have a single unique solution but a set of solutions. This redundancy results in a near infinite number of potential movement patterns which achieve the same end position. The degrees of freedom problem, as it has become known in the literature, is understanding how a single movement pattern is selected from the immense number of possibilities (Bernstein, 1967).

Even after a pattern is selected, the problem persists at the level of execution. The activation of these motor neurons must be orchestrated in such a way so as to produce coordinated motor action. There are many activation patterns which achieve the same result, the combinatorial expansion of possibilities is staggering.

It is important to note that such motor redundancy can be beneficial to the sensorimotor system. The degrees of freedom problem is a problem for scientists, not the system. A multitude of possible solutions makes the search for a single solution more likely to succeed; the inherent problem is understanding how this choice is made (Todorov, 2004). Because of this, Latash (2000) has argued that motor redundancy should actually be discussed as motor abundance.

A Functional Role for Variability

Although Bernstein (1967) originally posed the problem of motor control as the elimination of redundant degrees of freedom, Latash (2000) has proposed that the selective binding of abundant degrees of freedom is a more appropriate description. From this viewpoint, no degree of freedom is ever frozen or eliminated; rather, all elements contribute to all tasks. Irrespective of the terminology used, the redundancy~abundance of degrees of freedom is necessary for the adaptation of movements to perturbations. The result, a capacity to effect the same functional movement outcome in a number of different ways, is termed equifinality. The phenomenon was most notably observed by Kelso et al. (1984) in speech production and has since been documented in posture (Balasubramaniam et al., 2000), skiing (Vereijken et al., 1992), and reaching (Haggard et al., 1995). Equifinality permits adjustable, robust movements to be performed reliably. A central question remains then, regarding the mechanisms of equifinality. How are movement goals, environmental parameters and body state represented at a neural level and transformed into movement?

Gelfand and Tsetlin (1966) proposed that the central nervous system is organized in a hierarchy of structural units: groupings of elements transiently bound together by a common goal. These exist at all levels of analysis and the duration of what constitutes transient varies accordingly. In this model each unit specifies the relations between elements at a lower level. The relations among elements are task specific. This organizational structure distributes control and mitigates a large computational load being placed upon any single element. The principle of minimum interaction holds that any perturbation introduced by an element, that would result in an error in the common output, will be compensated for by the other elements. This prevents the need for a higher order structural unit to intervene with corrective action. Such systems, constituted by a task specific binding of elements, can be called synergies.

Although the term synergy has been used frequently and inconsistently in the literature, the modern definition has been most clearly put forth by Kelso (2009, p. 83) who states "a synergy is a functional grouping of structural elements…which, together with their supporting metabolic networks, are temporarily constrained to act as a single coherent unit." The central feature of a synergy is that a variation or perturbation to one member component will be immediately compensated for via covariation of one or more linked components. The components are bound together in a task specific way so as covariation among elements acts to stabilize a specified outcome value.

The system is structured hierarchically with cortical neural assemblies representing abstract goal level movement attributes. As signals progress through subcortical nuclei and eventually to the spinal cord, neural representations become less abstract and more specific until inputs are integrated onto the final pathways of motor neurons. The modern concept of hierarchical structure is reflective of Bernstein's conclusion that instead of controlling the specifics of joint or muscle action, the highest representation of movement in the nervous system encodes the spatiotemporal aspects of the movement.

This hypothetical concept has been modelled mathematically using geometric analyses. The uncontrolled manifold hypothesis or UCM (Scholz & Schoner, 1999; Scholz et al., 2000) and the minimum intervention principle or MIP (Todorov & Jordan, 2002) share several basic premises. The first premise is that an abundance of degrees of freedom in the neuromusculoskeletal system relative to those at the goal level creates an indeterminate system with a set of movement solutions. This solution set represents a subspace within the state space of all elemental variables and is presumed to have the structure of a n–dimensional manifold. The state space may consist, for example, of all possible end point coordinates, all possible joint rotations, or all possible levels of force. Each point on the manifold represents a unique combination of movement elements, collectively termed a movement solution, that result in the same outcome.

The second premise is that the controller will allow elements to vary freely along the manifold because within its subspace, different combinations of values result in a constant outcome. This minimizes control effort and satisfies the principle of minimum interaction. Values of elemental variables that lie outside the manifold are restricted, or controlled, to a greater extent because their variation compromises the stability of the intended movement outcome. The subspace along which greater variability is permitted is termed the uncontrolled manifold (Scholz & Schoner, 1999; Latash et al., 2002).

Points in the uncontrolled subspace do not affect the hypothesized control variable whereas different points in the orthogonal controlled subspace correspond to different values of the control variable. If variability in the uncontrolled subspace is greater than that in the controlled subspace, it is concluded the system operates synergistically.

The uncontrolled manifold hypothesis requires specific values of one or more outcome variables to stabilize. The controller of a multi element system defines both the relations between elements in the immediate lower level as well as specifying the value of their collective outcome variable. The hypothesis is fundamentally about the relations between elements. It does not require universal implementation; this mode of control may or may not be more effective than independent, non-synergistic control (Latash et al., 2002).

Stability

Central to the previous discussions is the concept of stability. Like synergy, the term stability has been used widely and inconsistently. Saltzman and Kelso (1987) reposed the classic degrees of freedom problem as a question of in which coordinate reference frame movements are planned. It is likely that the nervous system plans movements in whichever reference frame the description of movement trajectories is most stable (Scholz & Schoner, 1999). Stability in this case constitutes an ensemble of trajectories that is invariant and simple. If, for example, repeated movements result in highly consistent end point positions, it is likely that the system plans movement relative to the end point space. On the other hand, if repetitions of a movement produce highly stereotyped joint rotations, the movement is likely planned in joint space.

If an uncontrolled manifold is utilized for control, adjustments to the movement trajectory must occur in the controlled subspace. That is to say that only a variable such as a joint angle or configuration which is stable may receive a new assigned value. Scholz and Schoner (1999) define stability as "the capacity of the system to return to a given state after a perturbation has driven the system away from that state." Perturbations may be external, resulting from physical interactions with objects, fluids, or surfaces; or internal, resulting from complex multi–body musculoskeletal dynamics. The 'given state' of the system is called a fixed point or set point. Depending on the nature of the task, this set point can remain constant in time, as is the case in maintaining a posture, or change over time, as is the case during reaching movements and the rough terrain problem. If the set point is constant in time, variability is an indication of a stable system state. However, if the set point changes in time, as it does during adaptive locomotion, variability relative to time just measures the magnitude of set point change. In this case, stability of the system can be estimated by comparing the system across trials at the same relative point; more variability indicates less stability (Schoner & Kelso, 1990).

Synthesis in Ecological Context

It follows that if locomotion is a dynamic interaction between task, individual, and environment, then a salient feature of this interaction must function as a variable which is stabilized to facilitate the generation and execution of a movement plan or synergy. The rough terrain problem, as originally put forth by Warren (2007), was proposed as a special case of locomotor behaviour that involves ongoing instances of foothold selection and avoidance. However, within the evolutionary context of a gradual transition from arboreal brachiation to bipedalism, it seems likely that the mechanisms for locomotion over rough terrain represent a fundamental mode of functioning upon which typical modern unconstrained walking is based.

The selective pressures which drove the shift towards bipedal locomotion would have favored freeing the control system for other, higher level tasks. Persistence hunting for example, necessitates tracking prey over large distances. There would have been an advantage to free vision from the ground to maintain a bearing on the prey and for path integration of spatial position for navigation over the large distances covered.

Patla and Vickers (2003) demonstrated the capacity of the locomotor system to successfully make a series of constrained foot placements with gaze directed away from the ground immediately in front of the individual. It was reported that gaze was directed towards the ground less than 50% of the total travel time; the dominant behaviour was a travel gaze fixation. They hypothesized that in addition to environmental awareness, a travel gaze fixation generates relevant self–information from the optic flow field. The footprint constraints used by Patla and Vickers (2003) were however, of a visual nature only; an inaccurate foot placement had no physical consequences to the system and did not compromise continued movement.

The evolution of a system which promotes intermittent freeing of vision from the ground through sparing use of online feedback control during foot placement would permit an acceptable range of foot placement rather than requiring movement to a single point. The boundaries of an acceptable range of foot placement could then be a control variable for the dynamic stabilization of movement plans.

Problem

Adaptive locomotion describes any step or series of steps when purposeful alterations are made to the stereotypical gait pattern in order to satisfy environmental constraints. In modern contexts, adaptation of stepping is typically framed as a task performed in discrete chunks, between periods of unconstrained walking. This perspective is reflected in studies of adaptive locomotion which have primarily utilized locomotor pointing or obstacle avoidance experimental paradigms (Patla & Rietdyk, 1993; Patla, 1998; Bradshaw & Sparrow, 2001; Santos et al., 2010). The ensuing experimental manipulations of environmental and visual variables have provided insights into the control of constrained locomotion.

However, humans are capable of continuous locomotion over uneven terrain. The rough terrain problem is a general case of adaptive locomotion that encompasses the processes which underlie the sustained selection and execution of appropriate foot placements over uneven terrain. From a holistic perspective, the nature of the control strategy employed during locomotion over rough terrain remains unclear.

A facet of the rough terrain problem which has been the subject of relatively little study is the stepping stone scenario. This situation, in which discrete geometric features provide safe footholds over an unsuitable or otherwise hazardous background, can be thought of as the inverse of obstacle avoidance or as an extension of locomotor pointing involving sequential hard impacts over multiple targets. The stepping stone scenario represents an important mode of human locomotion, which is especially relevant in an evolutionary context. Despite this, little is known about the behaviour of the human locomotor system in such a condition. The problem then, in a general sense, is understanding how foot placements are selected and executed whilst walking over rough terrain utilizing discrete geometric features of the environment as footholds.

Purpose

This study specifically aims to investigate the relationship between geometric features of the walking surface and spatial patterns of movement variability in a stepping stone paradigm.

Design Rationale & General Hypothesis

An irregular walking surface affords the capacity for effective locomotion only in specific regions. Stepping within these regions facilitates continued locomotion whereas stepping outside these regions may increase the likelihood of injury or force locomotion to stop. Which physical features of the environment constitute these safe areas depends on their interaction with unique characteristics of the individual. The areas which offer the possibility for the action of stepping during continuous locomotion over rough terrain can be termed ‘locomotor affordances.’ This follows the language of Gibson (1977), who defined “the affordance of anything is a specific combination of the properties of its substance and its surfaces taken with reference to an animal.” As an example, Gibson posits that if a substance is sufficiently rigid, and its surface is sufficiently horizontal, flat, and extended, then it affords support to terrestrial animals and as a substratum is “stand-on-able” and potentially “walk-on-able.”

In this sense, specific attributes of a rough or uneven walking surface interact with characteristics of the individual to offer possibilities for foot placement. As a corollary, locomotor affordances also act as constraints on the behaviour of the individual. The ability to perceive and execute foot placements that satisfy these constraints is thus critical for safe and efficient bipedal locomotion over irregular ground. Within the literature, this criterion has commonly been referred to as the ability to make accurate foot placements. While this remains true and operational at a surface level, the term ‘accurate’ must be used with care.

It stands to reason that throughout the evolution of the locomotor system, there would have been very little selective advantage for a locomotor control system that optimizes foot swing trajectory to a single point within a locomotor affordance. Instead, any trajectory (or motor solution) which results in the foot landing within the locomotor affordance would be functionally equivalent. In order to assess motor behaviour on varying locomotor affordances, a walkway with interchangeable stepping blocks was designed to experimentally simulate bipedal walking over rough terrain such as a forest floor or savannah.

It is presently unknown precisely how the nervous system organizes a specific movement pattern when an abundance~redundancy of degrees of freedom exist in the locomotor system. Many different movement patterns would accomplish the same goal. In other words, many combinations of muscle activations and joint rotations will bring the foot into a given safe zone or locomotor affordance.

Because of this functional, or goal–level, equivalence, the perceptual motor system may not be trying to optimize accuracy to a point on the target in the traditional sense. It may instead be trying to optimize successful locomotion with minimal control effort exerted. End point precision may take a subsidiary role because unlike a loss of dynamic stability or forward progression, there are no significant negative consequences to low end point precision. Without a selective advantage for point based aiming, the system may utilize a form of area based aiming. Thus, an analysis of variability could give an indication of what variable is stabilized in such a scenario. If the relation of the foot to the boundaries of a locomotor affordance act as control variables, then observed end point variability should be greater along dimensions where the locomotor affordance offers more possibilities for foot placement. The general hypothesis is thus that the manipulated spatial constraints of locomotor affordances will determine, and be congruent with the spatial pattern of observed footfall variability.

Specific Hypotheses

1) Does the manipulation of target shape affect average walking velocity?

H_0 : Walking velocity will be equal across conditions

H_1 : Walking velocity will differ between conditions

2) Does the manipulation of target shape affect foot swing velocity?

H_0 : Swing velocity will be equal across conditions

H_1 : Swing velocity will differ between conditions

3) Does the shape of foot position variability reflect the shape of the target?

H_0 : No similarity in geometric pattern

H_1 : Similarity in geometric pattern

4) Does the manipulation of target shape affect the total foot placement variability?

H_0 : Total variability will be equal across conditions

H_1 : Total variability will differ between conditions

Furthermore, if the null is rejected it is hypothesized that pairwise comparisons will demonstrate total variability on:

No Block (C1) > Flat Square (C2)

Long Block (C3) > Wide Block (C4)

Flat Square (C6) > Raised Square (C5)

Chapter II. Methods

Participants

Twelve (4 male and 8 female) healthy adults participated in this experiment (median age = 24.3 years; range = 21 – 40). Participants self reported no visual, locomotor, or other sensorimotor impairments. Refer to Tables 2.1 and 2.2 for descriptive participant characteristics. The individuals were recruited from the University of Alberta community and received no compensation. All participants were volunteers who provided written informed consent. This study was approved by the PER–ALES–NS research ethics board at the University of Alberta.

Table 2.1 Summary of Participant Characteristics (N = 12)

Characteristic	M	SD
Age (years)	25.4	4.9
Height in Shoes (cm)	172.5	7.1
Length of Shoe (cm)	28.2	1.7
Height Barefoot (cm)	169.8	7.1
Length of Foot (cm)	24.1	1.7
Step Length (cm)	70.3	2.9

Table 2.2 Detailed Participant Characteristics

Participant Number	Sex	Age (years)	Height in Shoes (cm)	Length of Shoe (cm)	Height Barefoot (cm)	Length of Foot (cm)	Step Length (cm)
1	Male	40.1	185	30	182	24	75
2	Female	23.6	167	27	164	22	68
3	Female	25.3	168	25	165	22	69
4	Female	21.8	172	28	169	25	70
5	Female	23.9	169	27	166	22	69
6	Female	23.8	176	29	173	25	72
7	Male	27.3	183	30	180	26	75
8	Female	21.0	171	28	168	23	70
9	Male	22.8	170	30	167	26	69
10	Male	25.7	179	30	178	27	73
11	Female	24.7	160	26	158	23	65
12	Female	25.1	170	28	167	24	69

Experiment Setup and Apparatus

Testing took place in the Perceptual Motor Behaviour Laboratory at the University of Alberta. Participants walked along a wooden walkway measuring 117 centimetres wide by 484 centimetres long (Figure 3.1). The third panel of the walkway had two target locations, each of which accepted one of the stepping blocks described under experimental conditions. Metal pegs extending from the bottom surface of the stepping blocks would insert into holes drilled into the walkway. The stepping blocks could thus be securely placed in specific locations and orientations.

The first target location (T1) had a fixed location; blocks could be interchanged and rotated but not translated. The second target location (T2) could be translated along the anterior–posterior axis in 5 cm increments to accommodate varying step lengths of individual participants. The centre–to–centre width between T1 and T2 was fixed at 30 centimetres.

An approximate step length for each participant was predefined as a ratio of their height. To calculate step length, each participant's height in shoes was multiplied by a factor of 0.41 and then rounded to the nearest multiple of five (e.g. 70, 75, 80 cm, etc…). The starting position for each participant was marked with a piece of tape on the floor and set at a distance equal to three step lengths in front of T1. The inter–target distance was set equal to one step length.

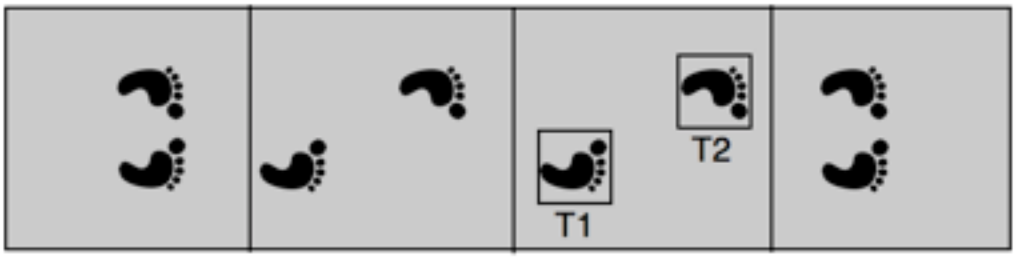


Figure 2.1 Diagram of walkway

Experimental Conditions

The setup of the walkway permits independent manipulation of the stepping blocks at Target 1 and Target 2. Each target has 5 possible block configurations:

• Long	Block is 40 cm long, 9.5 cm high, 6 cm wide
• Wide	Block is 6 cm long, 9.5 cm high, 40 cm wide
• Raised square	Block is 20 cm long, 9.5 cm high, 20 cm wide
• Flat square	Target is 20 cm long, 0 cm high, 20 cm wide
• No block	

Six combinations of stepping blocks were selected as the experimental conditions. The conditions were named C1 through C6 and are pictured in figure 2.2 below.

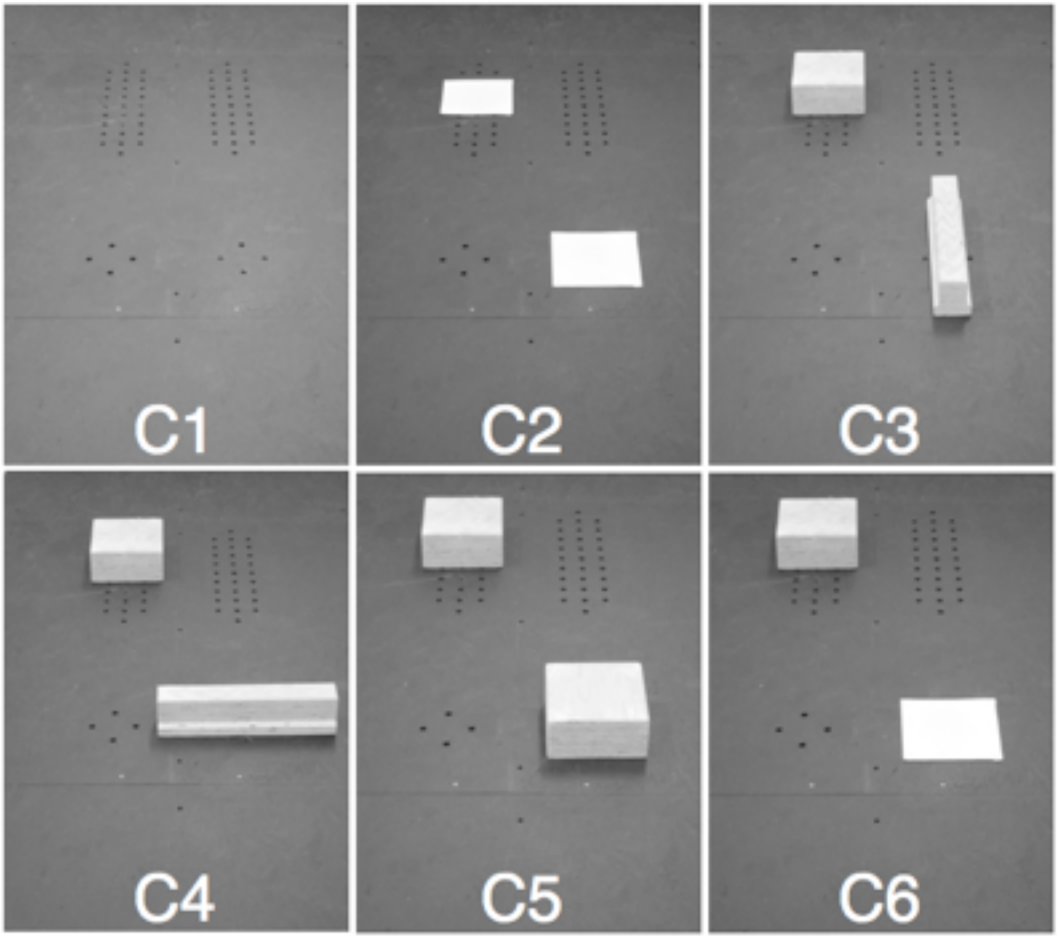


Figure 2.2 Photographs of target conditions

Design

A single factor repeated measures experimental design was utilized. Blocks of 25 trials were completed for each of the 6 conditions. Conditions 1 and 2 were always performed first and second respectively. The order in which the remaining 4 conditions were presented was counterbalanced to mitigate carry-over effects. Each participant completed all 6 conditions, for a total of 150 trials. Four different condition presentation sequences were created using a latin square such that each condition occupied each position in the sequence once, and the immediately preceding condition was completely crossed. Participants were randomly assigned to one of the four sequences. Refer to Table 2.3 for details of presentation sequence.

Table 2.3 Condition Presentation Sequence

Place in Sequence	Sequence 1	Sequence 2	Sequence 3	Sequence 4
First	C1			
Second	C2			
Third	C3	C4	C5	C6
Fourth	C6	C3	C4	C5
Fifth	C4	C5	C3	C3
Sixth	C5	C6	C6	C4
Participants Assigned	2, 3, 4	5, 7, 8	6, 9, 11	1, 10, 12

Participant Setup

After providing written informed consent, height and foot size were measured. Participants were then outfitted with optical LED motion capture markers. The markers were connected to a small control module and battery pack worn on a belt. Four markers were attached to each shoe on the following landmarks:

- Heel: midline heel of shoe
- Lateral: dorsum of foot above head of fifth metatarsal
- Medial: dorsum of foot above head of first metatarsal
- Toe: midline toe of shoe

Protocol

After a period of familiarization with the walkway, participants began the primary series of walking trials over the stepping blocks. Participants were instructed to start with their right foot and to ‘step on the blocks as you walk to the other end.’ Importantly this instruction did not include a requirement of accuracy or precision. After positioning themselves at the starting position, each trial would begin with an audible computer generated tone. Trials did not have a fixed duration so as to permit walking at a self selected pace. Recording was stopped manually when the participants reached the end of the walkway. Kinematics were recorded using a Visualeyez motion capture system (Phoenix Technologies Inc., Burnaby, Canada) sampling at 120 Hz.

Participants were permitted up to 4 practice trials to familiarize themselves with each experimental condition. If a participant started with their left foot, the trial was stopped and restarted. No incidents of missing or tripping on blocks were observed.

Data Reduction

Raw kinematic data were filtered using a second order low pass filter with a cut–off frequency of 8 Hz. Velocity was derived for the lateral foot markers. Step cycles were identified using a velocity threshold. Swing initiation was defined as the first of five consecutive frames in which velocity was greater than 20 centimetres per second. Swing termination was defined as the last of five consecutive frames in which velocity was less than 20 centimetres per second.

The starting position was designated as Stance 0. This was followed, for each foot, by Step 1, Stance 1, Step 2, Stance 2, Step 3, and Stance 3. Foot placements on the first and second targets were concomitant with Right Stance 2 and Left Stance 2 respectively.

The present analysis averaged the position of the lateral foot markers during each stance phase to obtain a two dimensional position of the foot in the horizontal plane.

Resulting outcome variables included:

- Movement Time, calculated as time from foot–off to subsequent foot–down for each step.
- Average Swing Velocity, calculated as the linear distance between position of foot–off to position of foot–down divided by the corresponding movement time.
- Foot Placement Variability, calculated as the independent anterior–posterior (AP) and medial–lateral (ML) standard deviations of step position over repeated trials for each stance number.
- Total Foot Placement Variability, calculated as the AP standard deviation multiplied by the ML standard deviation for each stance number.
- Constant Error of Foot Placement, calculated independently in each axis as the displacement between foot position and target centre averaged over all trials for a given stance number.

Chapter III. Results

Data were evaluated for normality with the Shapiro–Wilk test prior to analysis. Sphericity was assessed using Mauchly's test, and if violated, the degrees of freedom were conservatively adjusted using the Hunyh–Feldt correction. All omnibus tests were conducted using one–way repeated measures ANOVA at an alpha level of 0.05. Each of the six experimental conditions represented one level of the factor. Post–hoc pairwise comparisons were conducted where appropriate using repeated sample t-tests and evaluated against a critical value determined with a Bonferroni correction applied to maintain a family–wise alpha level of 0.05.

Average Walking Velocity

Figure 3.1 displays walking velocity data across conditions. For average walking velocity, Mauchly's test indicated the assumption of sphericity had been violated, $\chi^2(14) = 37.95$, $p < 0.05$. The degrees of freedom for the omnibus test were adjusted using Huynh–Feldt estimates of sphericity, $\varepsilon = 0.61$. The test revealed no significant differences between conditions, $F(3.047, 33.522) = 2.329$, $p = 0.091$, $\eta^2 = 0.175$, $\beta = 0.461$. Data from all conditions were collapsed to determine that participants walked with an average velocity of 1.19 m/s (SD = 0.10).

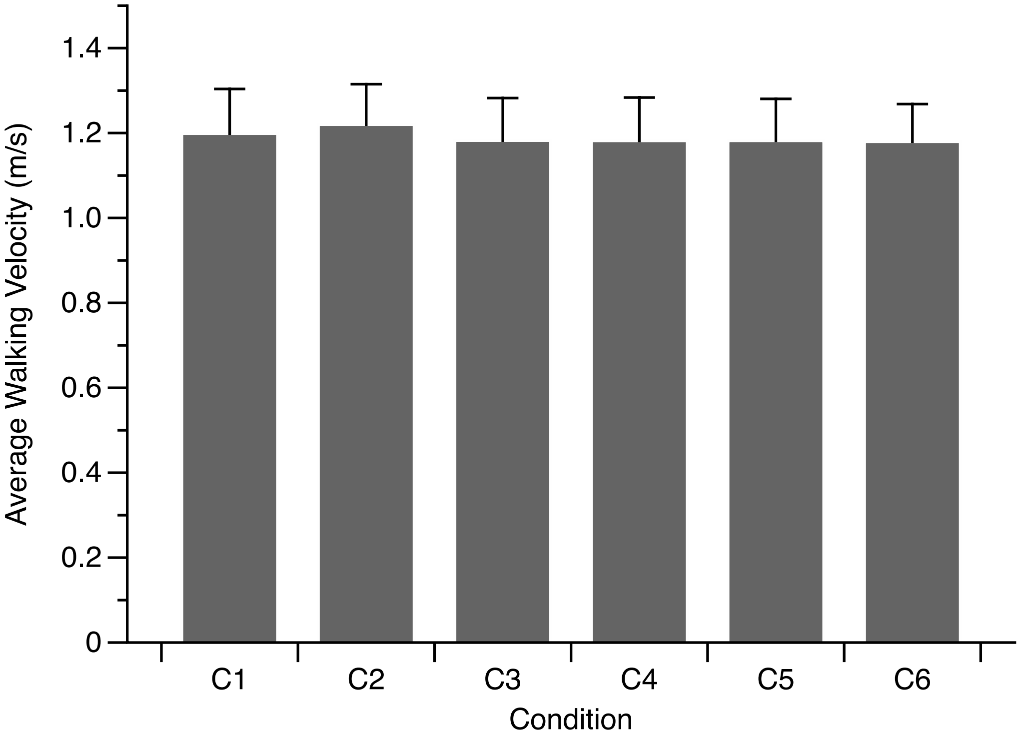


Figure 3.1 Average walking velocity along the anterior-posterior axis in metres per second.

Average Velocity of Feet During Adaptive Swing Phase

Figure 3.2 displays swing phase velocity data for the left and right feet. For the average velocity of the left foot during the adaptive swing phase, the omnibus test was statistically significant, $F(5, 55) = 16.22$, $p < 0.001$, $\eta^2 = 0.596$, $\beta < 0.001$. Planned comparisons were tested against a critical significance level of 0.0167. No significant difference was observed between conditions 1 and 2, $t(11) = -0.779$, $p > 0.0167$, $d = -0.22$, $\beta = 0.899$, or between conditions 3 and 4, $t(11) = 1.274$, $p > 0.0167$, $d = 0.37$, $\beta = 0.786$. However, left foot swing velocity in condition 5 (M = 2.11 m/s, SD = 0.15) was significantly slower than that observed in condition 6 (M = 2.35 m/s, SD = 0.16), *t*(11) = -6.714, $p < 0.0167$, d = 1.94, $\beta < 0.001$.

For the average velocity of the right foot during the adaptive swing phase, Mauchly's test indicated the assumption of sphericity had been violated, $\chi^2(14) = 35.70$, $p < 0.05$. The degrees of freedom for the omnibus test were adjusted using Huynh–Feldt estimates of sphericity, $\varepsilon = 0.583$. The omnibus test was statistically significant, *F*(2.914, 32.054) = 39.728, $p < 0.001$, $\eta^2 = 0.783$, $\beta < 0.001$. Planned comparisons were tested against a critical significance level of 0.0167. Although condition 1 (M = 2.29 m/s, SD = 0.18) was slower than condition 2 (M = 2.32 m/s, SD = 0.17), the difference was not statistically significant, *t*(11) = -2.731, $p > 0.0167$, d = -0.79, $\beta = 0.299$. Similarly, condition 3 (M = 2.53 m/s, SD = 0.17) was slower than condition 4 (M = 2.62 m/s, SD = 0.20); however, the difference was statistically significant, *t*(11) = -4.36, $p = 0.001$, d = -1.26 , $\beta = 0.023$. Right foot swing velocity in condition 5 (M = 2.51 m/s, SD = 0.16) was significantly faster than in condition 6 (M = 2.30 m/s, SD = 0.15), *t*(11) = 6.272, $p < 0.0167$, d = 1.81, $\beta < 0.001$.

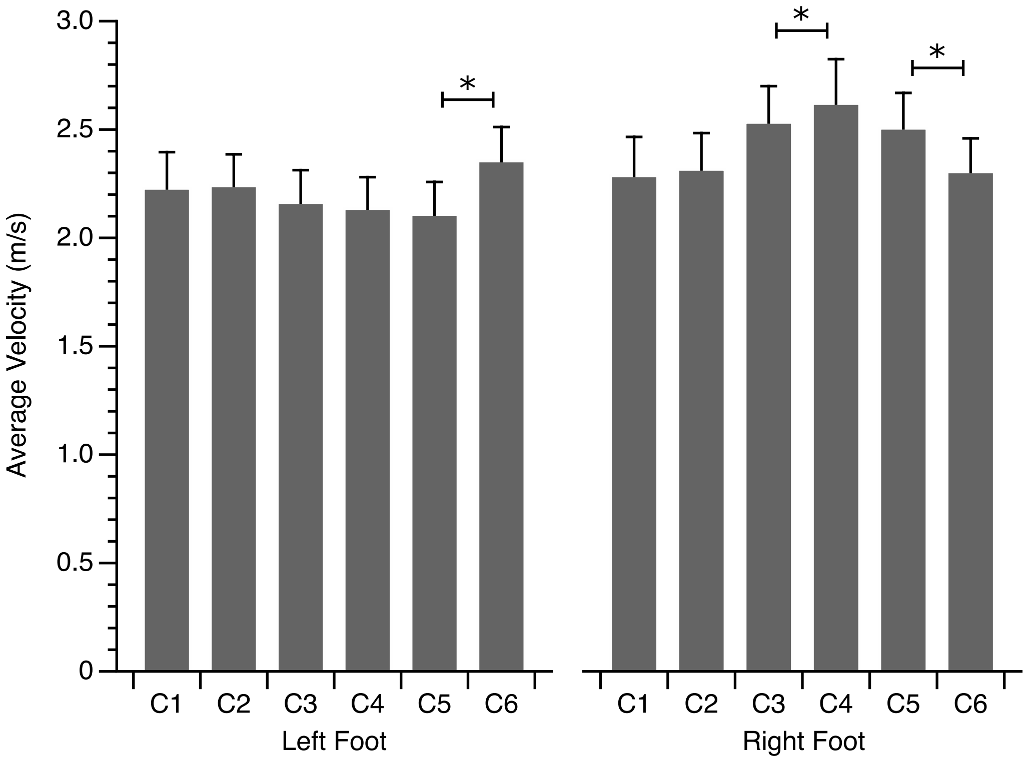


Figure 3.2 Average velocity of feet during adaptive swing phase.

Movement Time During Adaptive Swing Phase

Figure 3.3 displays movement time data for the left and right adaptive swing phase. The omnibus test for a main effect of condition on left foot movement time during adaptive swing was statistically significant, $F(5, 55) = 5.784$, $p < 0.001$, $\eta^2 = 0.345$, $\beta = 0.012$. Follow–up pairwise comparisons revealed no difference between conditions 1 and 2 (M = 0.645 s, SD = 0.047; M = 0.642 s, SD = 0.049 respectively), $t(11) = 0.628$, p = 0.543, d = 0.18 , $\beta = 0.911$, or between conditions 3 and 4 (M = 0.658 s, SD = 0.070; M = 0.667 s, SD = 0.0596 respectively), $t(11) = -0.940$, p = 0.367, d = -0.27 , $\beta = 0.862$. The comparison of conditions 5 and 6 did find that movement time in condition 5 (M = 0.685 s, SD =

0.072) was significantly longer than in condition 6 (M = 0.628 s, SD = 0.060), *t*(11) = 4.293, p = 0.001, d = 1.24, β = 0.027.

Right foot movement time also showed a significant main effect of condition, *F*(5, 55) = 34.225, $p < 0.001$, $\eta^2 = 0.757$, $\beta < 0.001$. Condition 1 (M = 0.632 s, SD = 0.051) was not different than condition 2 (M = 0.631 s, SD = 0.052), *t*(11) = 0.148, p = 0.885, d = 0.04 , β = 0.948. Condition 3 (M = 0.587 s, SD = 0.046) was significantly longer than condition 4 (M = 0.558 s, SD = 0.052), *t*(11) = 4.446, p = 0.001, d = 1.28, β = 0.019. Condition 5 (M = 0.591 s, SD = 0.049) was significantly shorter than condition 6 (M = 0.640 s, SD = 0.048), *t*(11) = -7.277, $p < 0.001$, d = -2.10, $\beta < 0.001$.

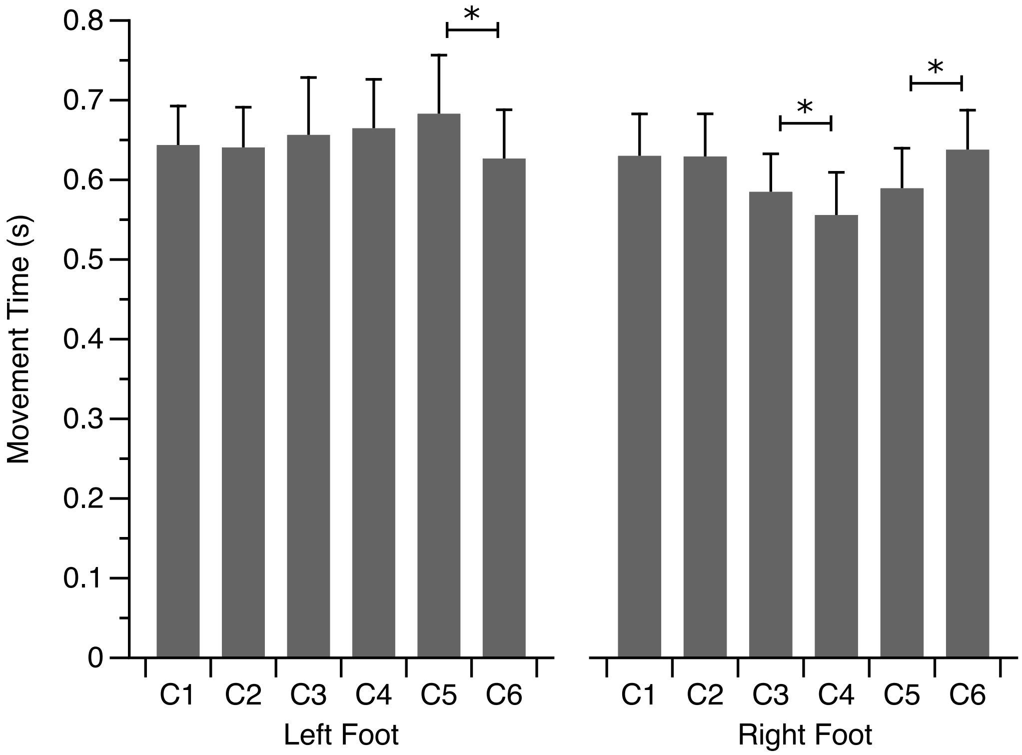


Figure 3.3 Movement time of feet during adaptive swing.

Spatial Relations of Foot Placement Variability on Targets

Figures 3.4 through 3.9 provide a visual representation of the footfall variability data. The scale of the axes is equivalent so as to accurately display the spatial relations from a top–down perspective. Each figure plots the variability of static foot position during stance phase on the left and right targets. The centre of the target is represented by the origin of the plot. Each set of crosshairs corresponds to a single participant. Variability of foot placement on the anterior–posterior axis is represented by the vertical error bars. Medial–lateral variability is represented by horizontal error bars. The intersection of the error bars is located at the average position of the foot relative to the centre of the target. Average position was calculated using the procedure for constant error relative to the centre of the target. Variability was calculated as the standard deviation of position in the respective axes. No statistical tests are represented in the figures.

Figure 3.11 displays the pooled variability data from all participants for each step in each condition. Anterior–posterior variability is presented across the top row in panels 1–4 for left step 1, left step 2, right step 1, and right step 2 respectively. The corresponding medial–lateral variability data are presented across the bottom row in panels 5–6.

Pearson product moment correlations between anterior–posterior position and medial–lateral position for the feet on target are presented in appendices A and B.

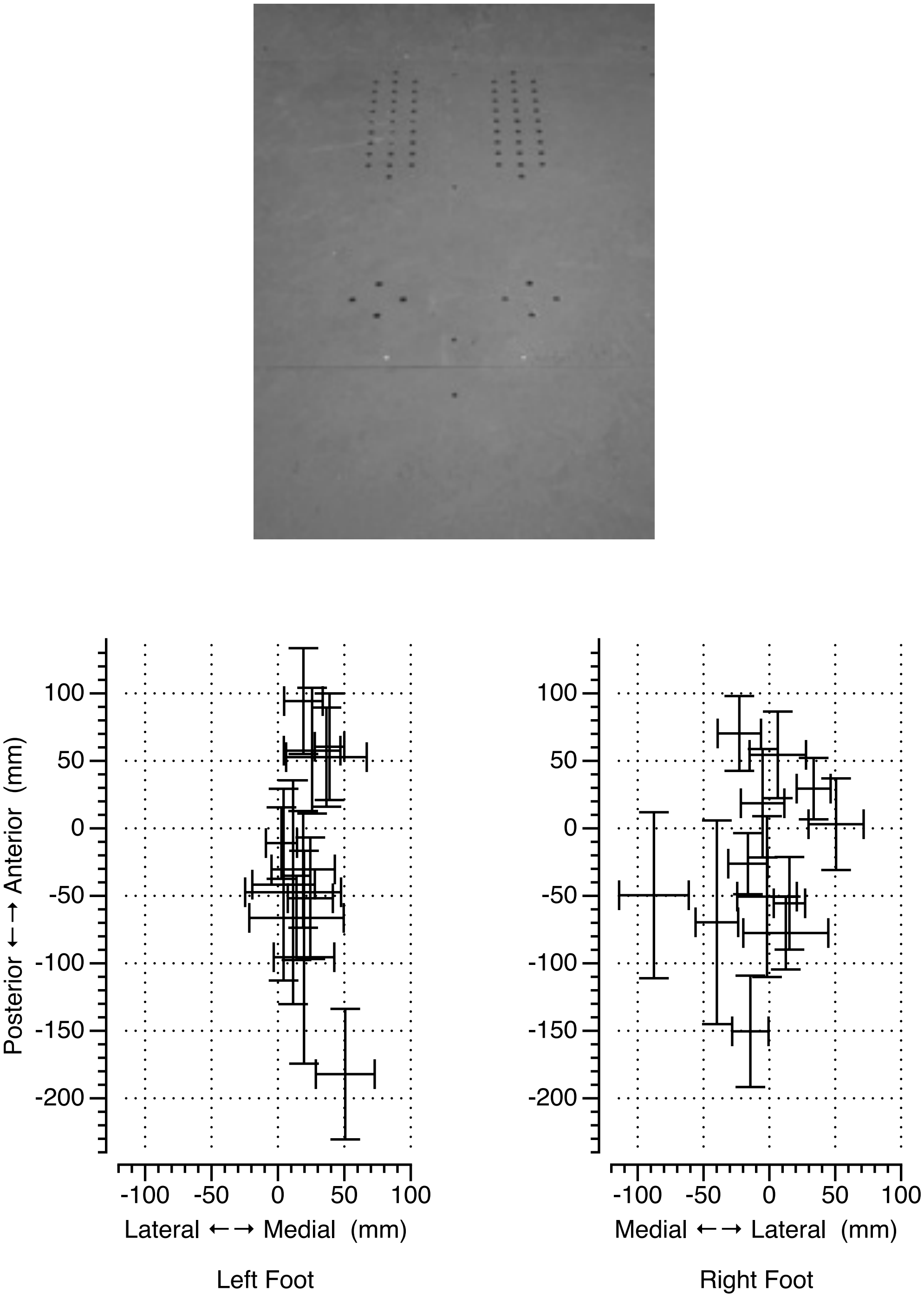
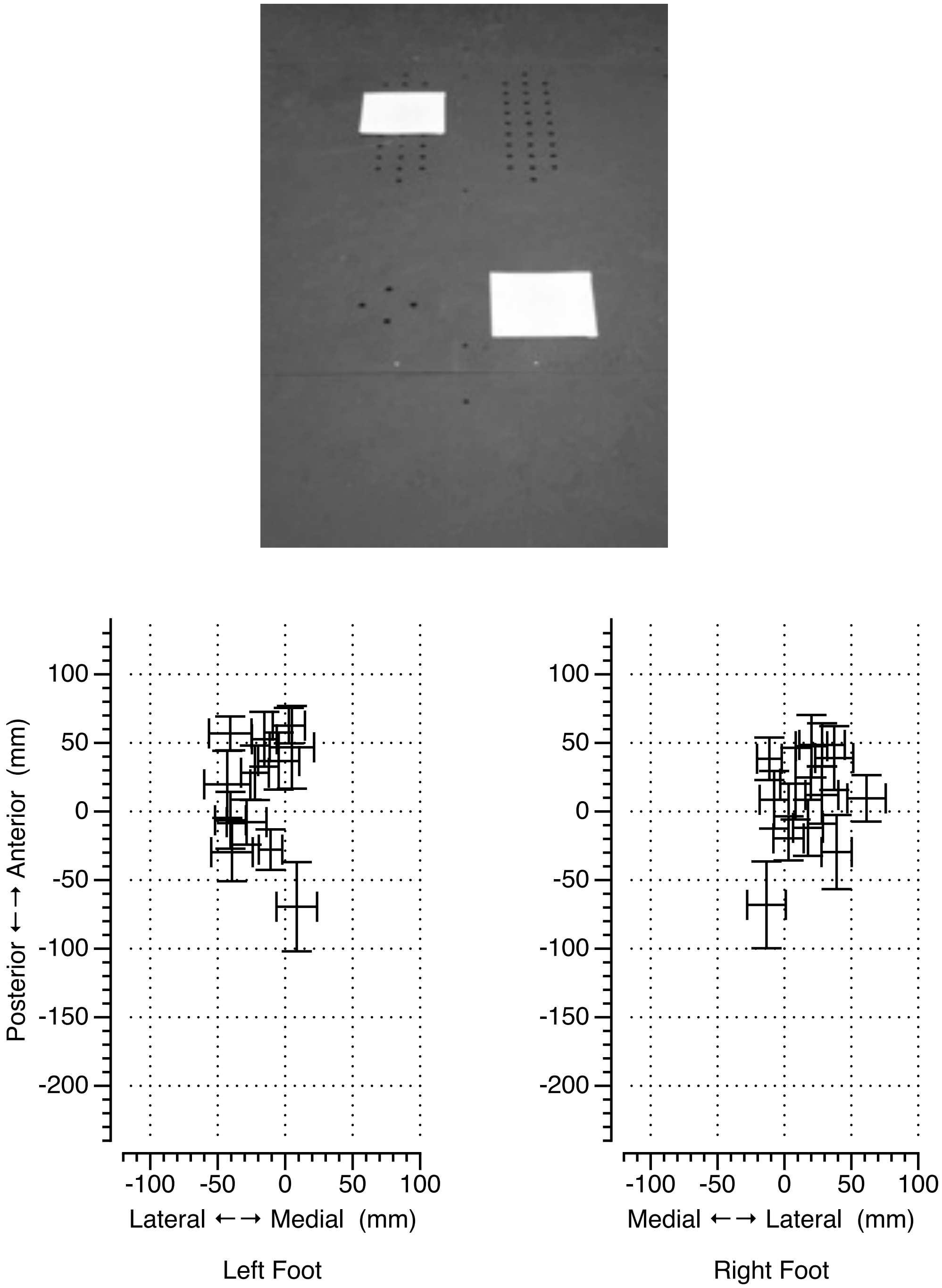


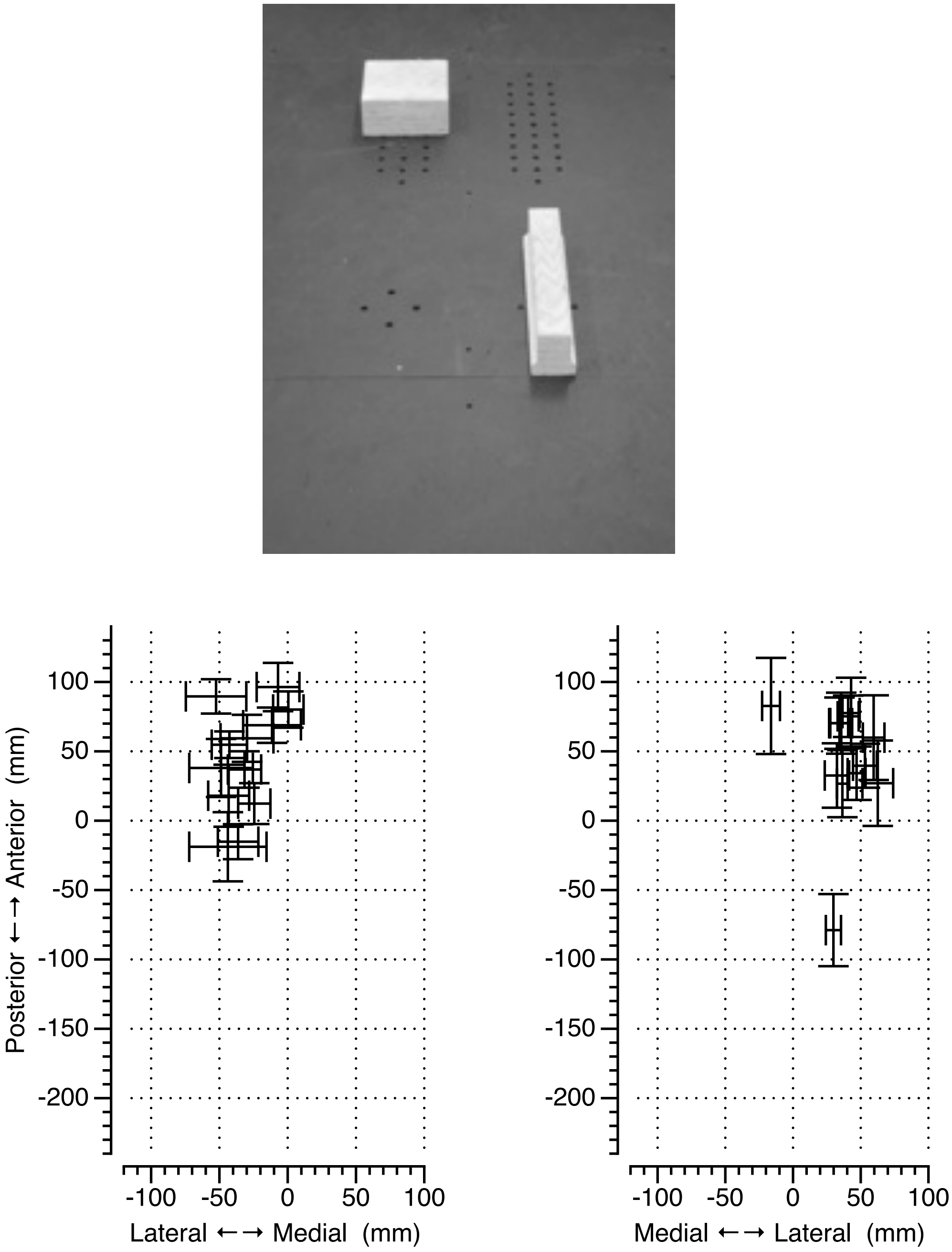
Figure 3.4 Variability pattern for condition 1.



Left Foot

Right Foot

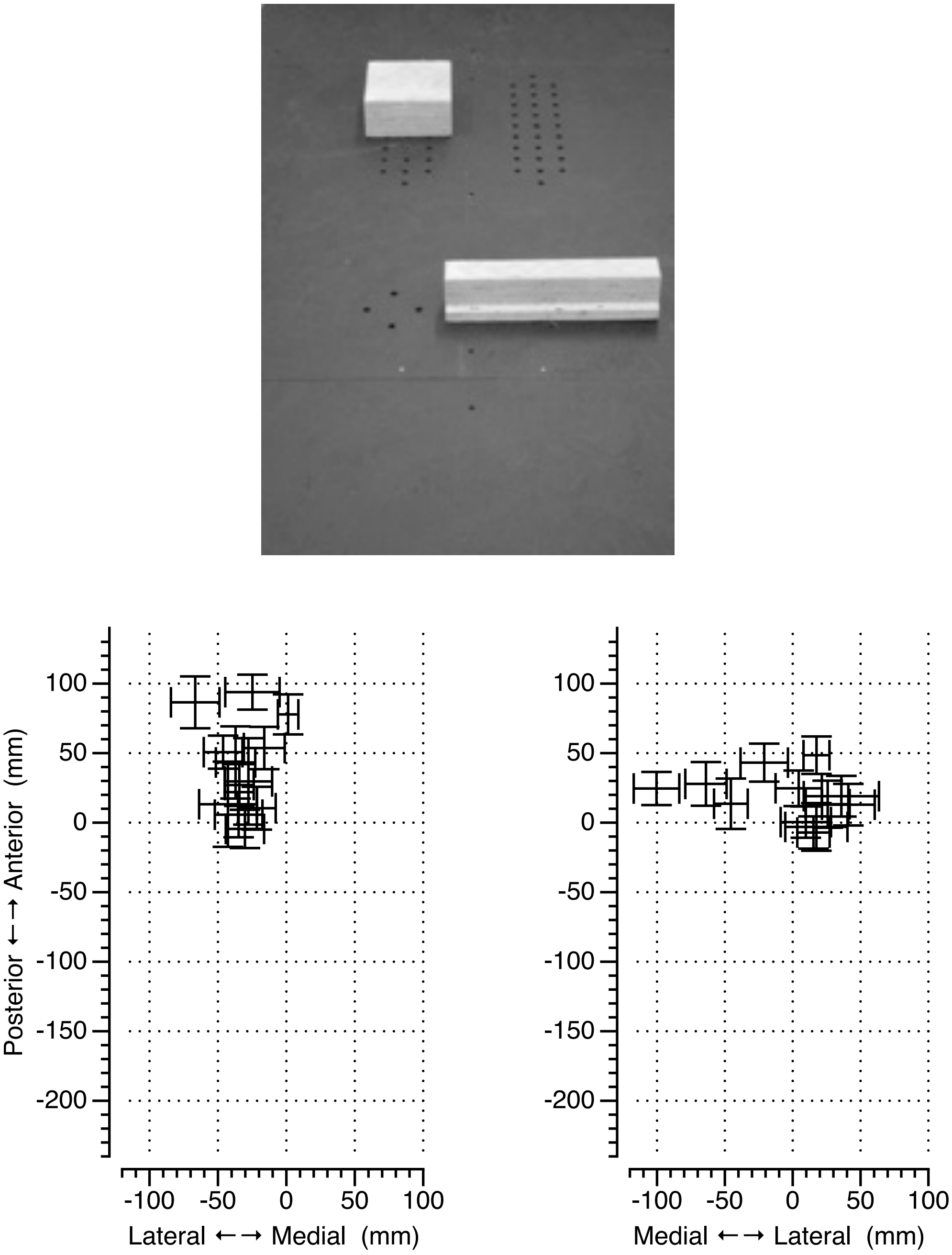
Figure 3.5 Variability pattern for condition 2.



Left Foot

Right Foot

Figure 3.6 Variability pattern for condition 3.



Left Foot

Right Foot

Figure 3.7 Variability pattern for condition 4.

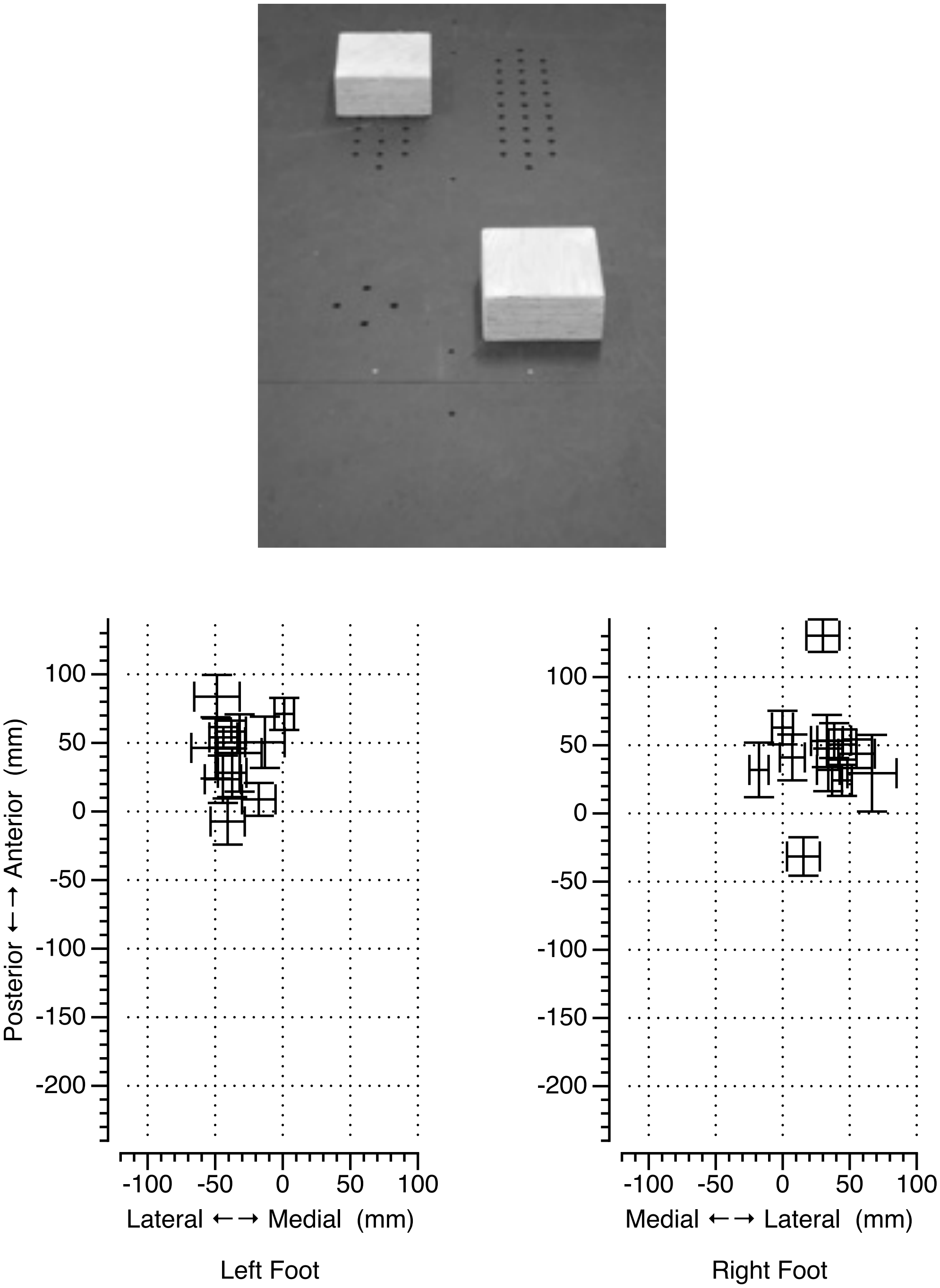


Figure 3.8 Variability pattern for condition 5.

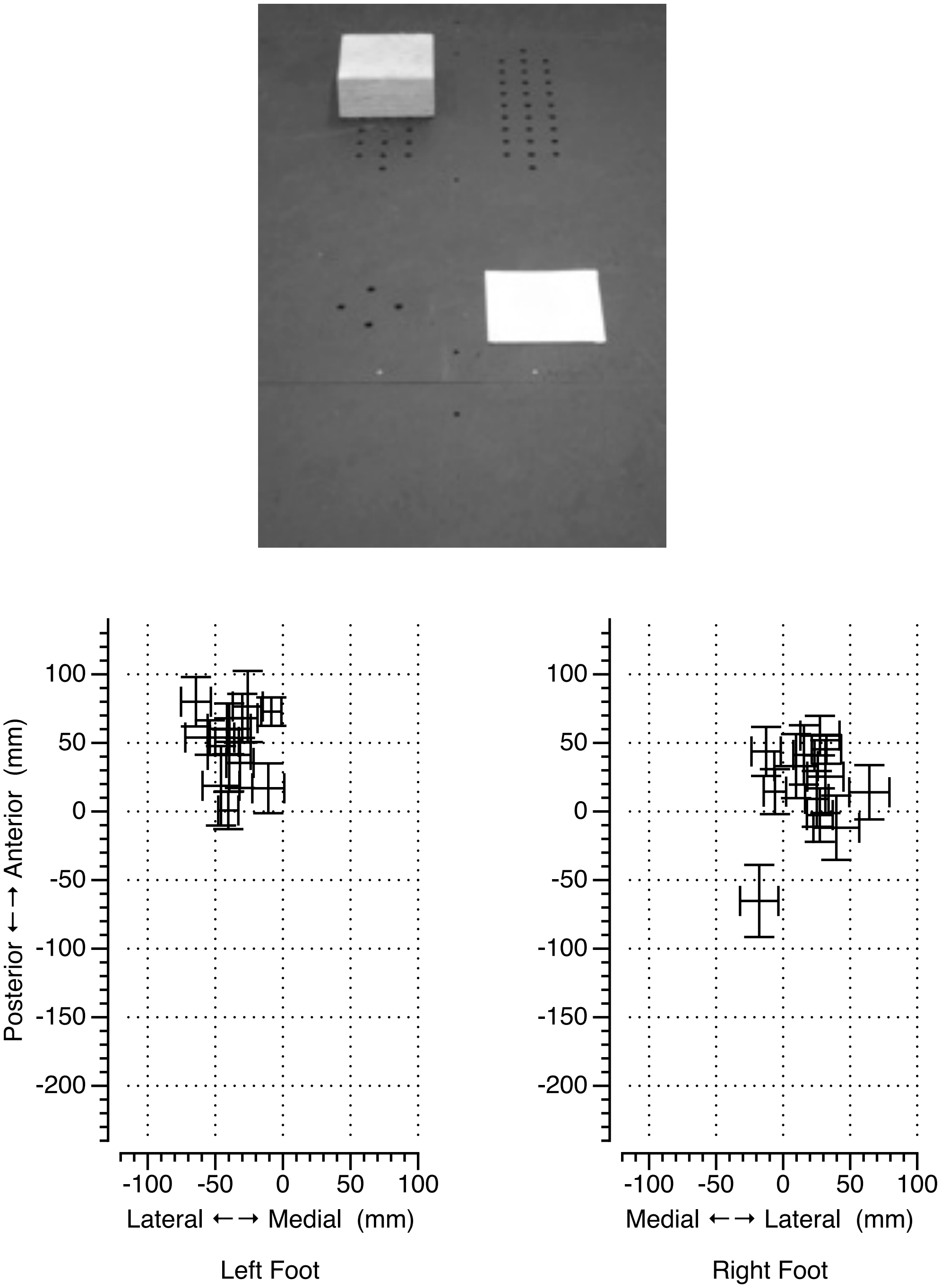


Figure 3.9 Variability pattern for condition 6.

Total Variability of Right Foot on Target

Figure 3.10 plots total foot placement variability. For total variability of the right foot on target (see figure 3.10; panel 4; Right Step 2), Mauchly's test indicated the assumption of sphericity had been violated, $\chi^2(14) = 67.07$, $p < 0.001$. The degrees of freedom for the omnibus test were adjusted using Huynh–Feldt estimates of sphericity, $\varepsilon = 0.278$. The omnibus test for a main effect of condition on total variability for the right foot was significant, $F(1.391, 15.297) = 17.032$, $p < 0.001$, $\eta^2 = 0.608$, $\beta = 0.009$. Follow–up comparisons revealed differences between conditions 1 and 2 (M = 766.06 mm^2, SD = 424.77; M = 267.35 mm^2, SD = 79.15), $t(11) = 3.968$, $p = 0.002$, d = 1.15, $\beta = 0.05$. The difference between conditions 3 and 4 (M = 177.85 mm^2, SD = 70.59; M = 246.63 mm^2, SD = 85.24) was also found to be significant, $t(11) = -3.463$, $p = 0.005$, d = -1.00, $\beta = 0.117$. The difference observed between conditions 5 and 6 (M = 174.42 mm^2, SD = 113.67; M = 250.47 mm^2, SD = 104.27) did not reach statistical significance, $t(11) = -1.805$, $p = 0.099$, d = -0.52, $\beta = 0.622$.

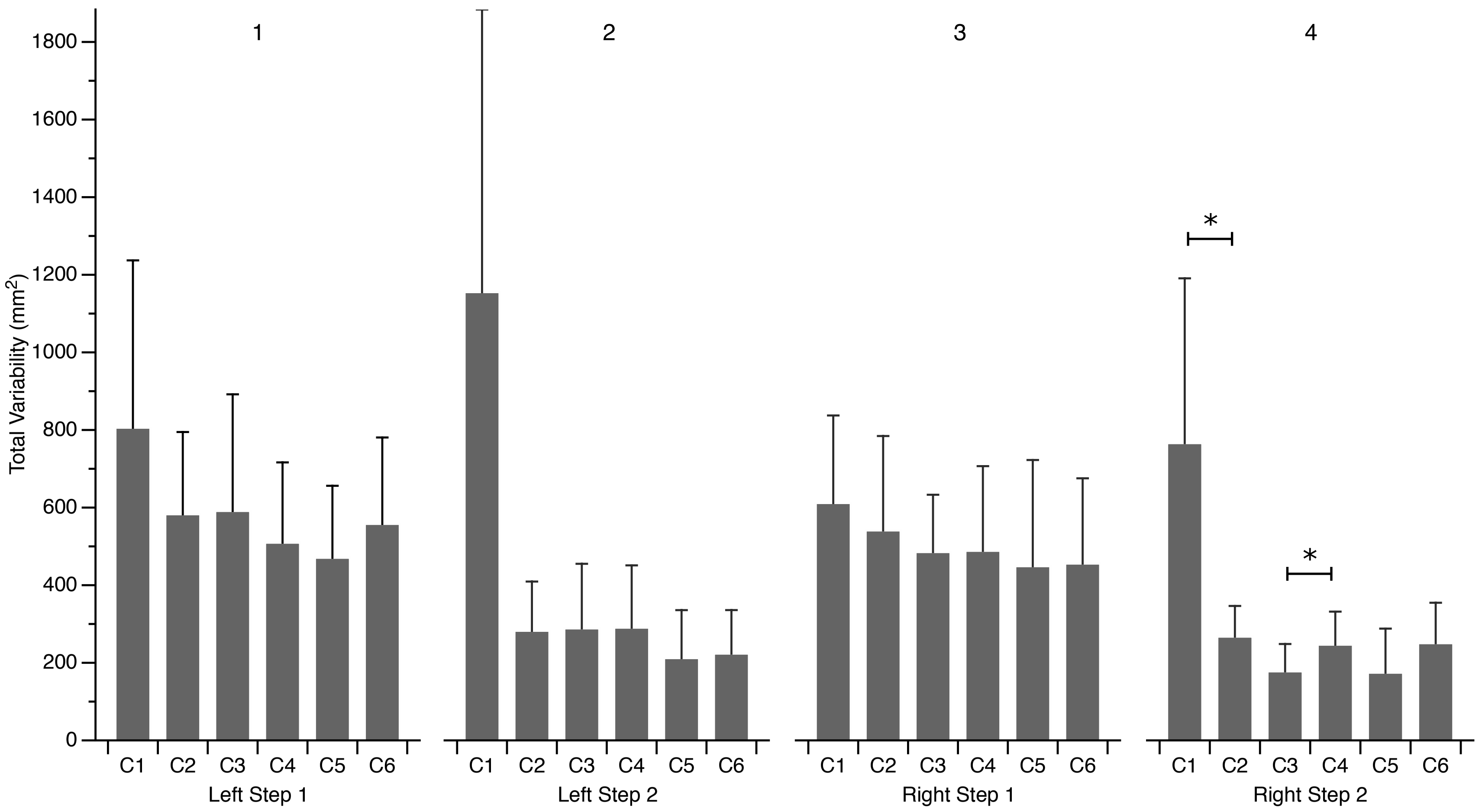


Figure 3.10 Total variability of foot position calculated as the product of variability in the A–P and M–L axes.

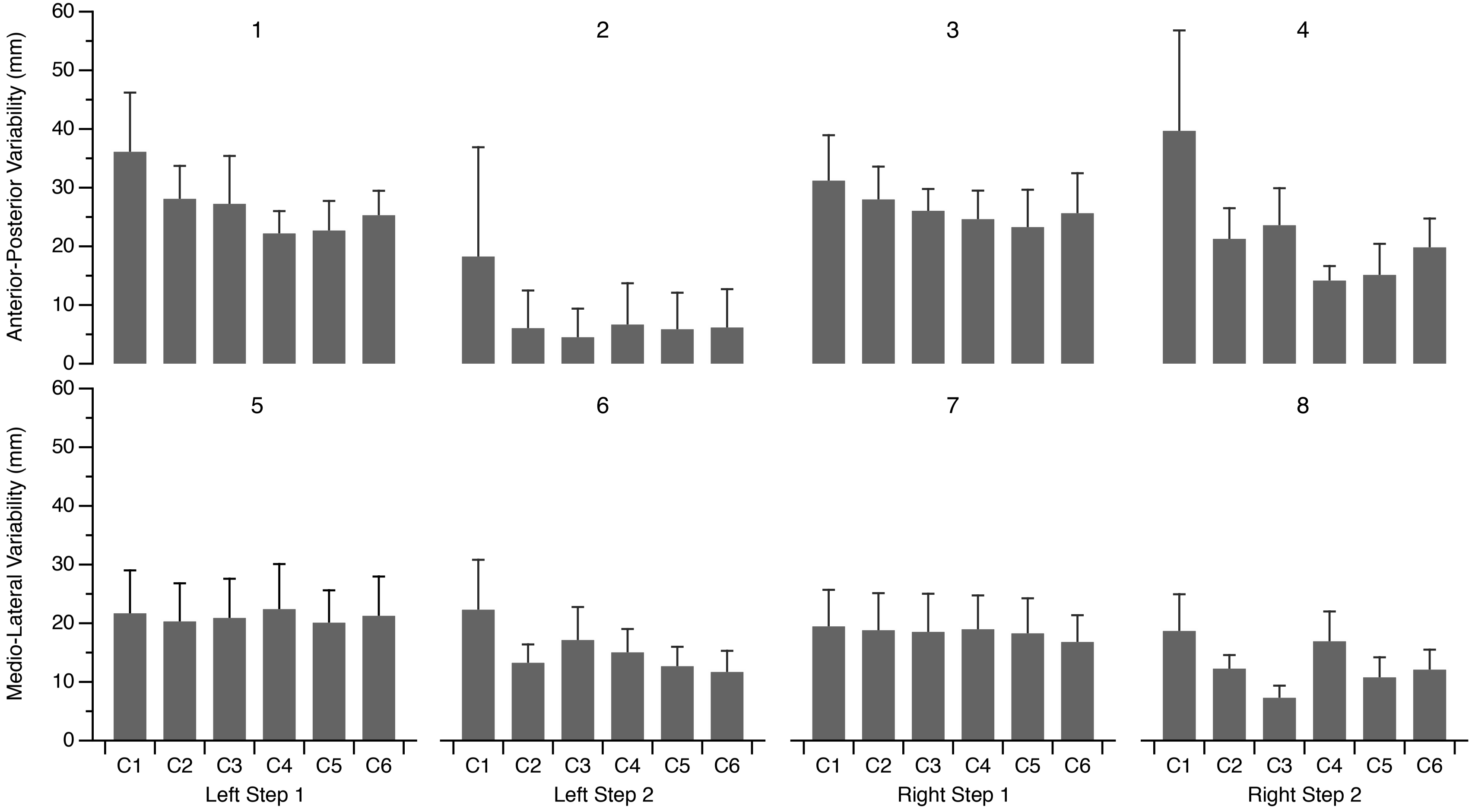


Figure 3.11 Variability of foot position calculated as the standard deviation of position in the A–P and M–L axes.

Chapter IV. Discussion

The aim of this study was to create an experimental simulation of rough terrain that might be encountered in a natural environment such as a forest. When walking over rough terrain, physical features of the ground like tree roots, rocks, or depressions impose constraints on foot placement with some areas affording safe and effective footholds while others present hazardous and ineffective foot placement possibilities. Humans are able to adapt their locomotor patterns to walk over rough terrain in a continuous, fluid fashion; however this process is not well understood. This study investigated an aspect of the rough terrain problem by creating a stepping stone scenario in which raised geometric objects, or stepping blocks, acted as a series of positive footholds. The height and shape of the stepping blocks was manipulated to assess its effect on stepping behaviour. It was hypothesized that the locomotor system would stabilize foot placement anywhere on the block rather than to a specific point on the block thus resulting in footfall variability patterns that reflect the shape of the associated stepping block. The constituent outcome variables and statistical tests, along with their relevance to the existing literature, are discussed in the following sections.

Average Walking Velocity

The null hypothesis that walking velocity will be equal across conditions cannot be rejected. The consistency observed in walking velocity across conditions indicates that the constraints imposed by the experimental conditions did not exceed the capacity of the system for adaptation during a typical mode of walking. An absence of differences in walking velocity between conditions is not surprising considering the participants started from a stationary position and completed approximately six steps. This makes it likely that participants remained in an accelerative phase over the course of each trial and did not attain steady state locomotion. Coupled with the unique character of the experimental setup, the lack of steady state velocity data makes it difficult to compare the present results to either those from other studies within the adaptive locomotion literature, or published normative data.

If the capacity of the system for adaptation had been stressed, it is expected that movement would have been slowed to facilitate foot placements with sufficient accuracy on more difficult targets. For aiming tasks in general, it is accepted that smaller targets create a greater index of difficulty and result in slower movements (Fitts, 1954). Such a speed–accuracy tradeoff was documented in a series of locomotor pointing experiments conducted by Bradshaw and Sparrow (2001, 2002) in which approach velocity and target length were manipulated respectively. In the first study they reported a linear trend between increasing approach velocity and decreasing accuracy on the target. In the follow up experiment, a linear trend was reported between increased target length and increased accuracy while velocity was maintained constant. The direct applicability of their findings to the present study is limited because the increased velocities were achieved with jogging and sprinting gaits, and the target consisted of a single take off board. This withstanding, there is reason to expect future work could provide an indication of the relative difficulty of the target conditions used in the present study by measuring the maximum approach velocity at which the locomotor affordances could be reliably used.

However, the purpose of this study was not to evaluate the relative difficulty of stepping blocks in a hard impact targeting scenario but rather to examine how they are used during a more continuous mode of locomotion. With respect to this objective, the consistent observation of a walking velocity of 1.19 metres per second across conditions permits the elimination of walking velocity as a confounding variable. Because the same average walking velocity can result from varying combinations of swing and stance phase parameters from step to step, a speed–accuracy tradeoff could also be present at the level of individual steps. Thus a more thorough analysis was carried out beginning with swing phase velocities of the feet.

Average Velocity of Feet During Swing Phase

With regard to the left foot, the only statistically significant follow–up test resulted from the comparison of the raised square of condition 5, which was the slowest leg swing measured, and the flat square of condition 6, which was the fastest leg swing measured. Inspection of figure 3.2 places this difference in context; the velocities measured in the long block and wide block conditions (C3 and C4 respectively) while not significantly different from each other, are closer in value to the slow swing of condition 5 than to the fast swing of condition 6. Although the statistical design did not permit further post hoc analysis of this relationship, some inferences can still be drawn. Since the left foot took off from the walkway surface and landed on the raised square at T2 in all four of these conditions, any differences in swing velocity can be attributed to the state of T1. In conditions 3, 4, and 5, both T1 and T2 were raised blocks; however condition 6 was the only circumstance where T1 was flat and T2 was raised. This means that swinging the foot from the surface of the walkway to the raised block when the contralateral support foot was at the level of the walkway resulted in the faster velocity. The movement strategy employed during a leg swing to a higher surface therefore involves modulation of swing velocity.

This pattern also appears to persist in the data for the right foot. If a swing from the walkway surface to a raised block while the support leg is on the walkway surface results in faster swing velocities, one would expect conditions 3, 4, and 5 to exhibit the fastest average swing velocities. The right foot data support this conjecture as the velocities measured in these three conditions are faster than the conditions in which the right foot did not step to a raised block. Although stepping onto the raised square of condition 5 was significantly faster than stepping onto the equivalent flat square of condition 6, the other planned comparisons did not fully capture this effect and future work should address this limitation.

Furthermore, the velocity data for conditions 1 and 2 were consistent across both limbs between 2.2 and 2.3 m/s. This indicates firstly, that alterations in swing velocity are largely due to the elevation change associated with the raised blocks and secondly, that the experimental protocol did not give rise to qualitatively different behaviours between the two targets. This consistency, combined with the finding of equivalent walking velocities across conditions, demonstrates the soundness of the protocol insomuch that it elicits observable differences in stepping behaviour without excessively constraining the system and causing a shift to an atypical mode of locomotion.

The statistically significant difference between conditions 5 and 6 in both the right and left limbs may be indicative of a more general phenomenon in which faster foot swing velocities are produced when stepping onto a raised block. The elevation increase associated with stepping onto a raised block requires a leg swing with more kinetic energy. This could be achieved by applying a greater impulse to the leg, presumably by modulating the force generated by the hip flexors during early swing phase. This strategy retains the temporal characteristics of typical muscle activation patterns by increasing only the force parameter. Because the impulse is applied in a ballistic fashion, greater velocities are generated. The alternative approach would be to apply a more modest force over a longer period of time. Although this strategy would potentially be more energy efficient, it would also require greater control effort to modulate the force and time characteristics of the unique trajectory. The system would in essence need to operate in an online control mode. This scenario implies that uninterrupted forward progression is prioritized over energy efficiency of individual steps, which is consistent with the the hierarchy of criteria which are applied to determine alternative foot placement selection (Moraes et al., 2007).

Another consideration is that an increased velocity early in swing gets the foot through most of the distance and near the target with extra time to make corrections if necessary. This strategy would be consistent with the observation of greater than necessary clearance margins during obstacle avoidance (von Hedel et al., 2002; Santos et al., 2010). In both situations, a conservative approach is taken in which the limb is elevated in excess of the height of the obstacle in order to ensure the integrity of the system and its capacity to continue walking. In most real world rough terrain scenarios, it is likely that instances of obstacle avoidance and obstacle targeting are intermixed along a continuum of environmental features in which some have the potential to function both as obstacles to be avoided or as stepping stones. Evolutionary adaptations to this type of environment necessitate a robust and flexible control system that does not need to categorize environmental features and ‘switch modes’ from step to step. Instead, adopting a strategy that functions for both situations simplifies control and satisfies the principle of minimal intervention. The slower left foot velocities measured in conditions 3, 4, and 5, where both targets were raised blocks, could reflect an absence of this conservative limb elevation strategy. This could be due to a reduced uncertainty regarding the nature of the feature; the block at T2 no longer functions as an obstacle to be avoided because its height is the same as T1 and thus becomes accessible via a typical less constrained step. Accepting the premise that the primary determinant of alternate foot placement selection is minimum displacement, if the block at T2 affords a sufficient foot hold, it becomes the default target for the left foot. No 'mode switching' is necessary as the circumstances have negated the need for a decision.

Although intuitive, these explanations are speculative. They are dependent upon perceptual information regarding the relation of the environmental features to those of the individual. Although the literature on the role of vision during adaptive locomotion would generally support this as probable (Mohaghegi et al., 2004; Moraes et al., 2007).

Movement Time During Adaptive Swing Phase

The data for movement time provide corroborating evidence for the previous interpretations of swing velocity (see figure 3.3). A statistically significant difference in movement time for the left foot between condition 5 and condition 6 mirrors the test carried out on velocity. The slower velocity in condition 5 was associated with the greatest movement time and the faster velocity in condition 6 was associated least movement time. This is to be expected if one assumes a similar step length across conditions. The possibility of differences in step length accounting for the observed differences in movement time is unlikely considering the targeting steps were the third and fourth in the series for the right and left feet respectively, and the start position was fixed.

The data for right foot movement times also support the trend. The greater velocities in conditions 4 and 5 relative to conditions 3 and 6 respectively are mirrored by significantly shorter movement times in the same comparisons. The faster leg swings in conditions when the foot landed at a higher elevation than where it took off were previously supposed to have resulted from a limb elevation strategy that provides extra time with the foot in the vicinity of the target so as to permit corrections if necessary. The short movement times observed in these same conditions indicate that if this were the case, the potential extra time was not utilized. It is not clear precisely what circumstances would require full use of the available time and result in an initial rapid ballistic movement followed by a slow hovering of the foot over the target. Based on the collective body of aiming literature, we can presume that factors which would otherwise result in inaccurate movements, such as to a lack of information, error of perception, or perturbation, would result in a longer duration leg swing (see Schmidt & Lee, 2005).

Spatial Relations of Foot Placement Variability on Targets

The general hypothesis of this study was that the manipulated spatial constraints of the locomotor affordances will determine the spatial pattern of observed footfall variability. It was thus expected that the relation between anterior–posterior variability and medial–lateral variability would be congruent with the respective dimensions of each target block. Unfortunately there is not currently an accepted method for quantitatively assessing the geometric congruence of the data or for applying inferential statistics to the data. As an exploratory analysis, the standard deviation of footfall position was calculated as a measure of variability; however, it is not clear if this is the most appropriate operation. Along the same line it is not known whether a standard statistical procedure such as ANOVA would permit meaningful conclusions to be drawn. To this end, no inferential tests were conducted on the spatial variability along the independent axes. The data, pooled across participants, are presented in figure 3.11 for reference. Limitations withstanding, the results generally appear to support the hypothesis; visual inspection of variability patterns in figures 3.4 through 3.9 reveals similarities when compared to their respective target shapes presented in figure 2.2. The null hypothesis that there would be no similarity between the geometric patterns of the spatial constraints and footfall variability can thus tentatively be rejected.

The data from condition 1, in which no targets were present, provide a reference by demonstrating the patterns arising from unconstrained locomotion over a level walkway (figure 3.4). Foot placements were much more variable in the anterior–posterior plane. This would be expected as the majority of locomotor movements occur parallel to the direction of travel in the sagittal plane. The magnitude and ratio of variability appears to be consistent between both limbs however the distribution of average left foot positions is grouped more tightly along the medial–lateral axis. Despite instructions to walk freely, it cannot be ruled out that participants used the row of indexing holes in the walkway as a visual reference which drew the foot placements in line. The phenomenon could also be an artifact of the short walkway distance. The right foot placement occurs closer to the beginning of the trial in a more accelerative phase when the body has less forward momentum and thus the distribution is wider. The system is one step closer to steady state locomotion by the left foot placement and a tighter distribution results from the locomotor rhythm stabilizing.

Condition 2 was designed to provide a reference for the effect of visual cues without corresponding physical constraints or consequences. It is obvious from figure 3.5 that the inclusion of flat, square visual targets with instructions to step on them had a marked impact on footfall variability. As expected, the visual targets resulted in more consistent foot placements over repeated trials. Compared to condition 1, the largest differences were in the anterior–posterior axis where right foot placement variability decreased by approximately 50% (figure 3.11, panel 4) and left foot variability decreased by approximately 70% (figure 3.11, panel 2). Reductions in medial–lateral variability were present but more modest. Consistent with the hypothesis that there would be a similarity in geometric patterns, the combined effect resulted in variability patterns that more closely resembled the square shape of the targets compared to the distinct rectangular pattern in condition 1.

The flat square placed at T2 in condition 2 was changed to a raised square in the remaining four experimental conditions. The manipulation did not have a noticeable impact on the shape or magnitude of footfall variability (see left foot panels of figures 3.6 through 3.9 as well as panels 2 and 6 of figure 3.11). The consistency across conditions 3, 4, 5, and 6 is to be expected. It was however, hypothesized that variability on a raised square would be less than that measured on a flat square of the same dimensions. It was reasoned that while providing the same amount of visual information, the difference in height would impose physical consequences to foot placement and therefor result in a tighter grouping of foot position. The absence of a substantial effect implies that there was not a direct perception of the additional affordance provided by the flat square as would be predicted by Gibson (1977). Alternately, the dimensions of the square may not have provided strong enough constraints to induce a change in stepping behaviour.

The most notable effects of the experimental manipulations are evident in the right footfall variability patterns in conditions 3, 4, and 5 (figures 3.6, 3.7, & 3.8). The 'long' block orientation of condition 3 resulted in dramatically narrowed footfall variability. While this superficially supports the hypothesis, in reality there was little possibility for a different result; the magnitude of the standard deviation is limited by the dichotomous nature of stepping either on or off of the block. The more interesting finding is the expansion of variability along the anterior–posterior axis. As expected, participants successfully completed all trials with similar speed but constrained their foot placements along this axis to a greater extent in both conditions 2 and 6, when the flat target did not physically limit foot placement. Panel 4 of figure 3.11 displays the greater anterior–posterior variability in C3 relative to both C2 and C6. This shows that the control was exerted independently along each axis. Results from conditions 2 and 6 demonstrate it is possible to make more precise steps even in the absence of a strong physical constraint. If foot placement selection was being optimized to a point, one would expect the narrow lateral constraint of condition 3 to tether foot placement along the anterior–posterior axis into a tighter area. Observation of the opposite effect demonstrates the control system is using the available surface area of the block even if it has the capacity to constrain foot placements closer to the centre without compromising other parameters. This strategy maximizes the probability of a successful foot placement and minimizes the need for intervention. The binary nature of stepping on these locomotor affordances could cause the block edges to act as boundary conditions in which movement patterns stabilize (Kelso, 1995; Beer, 2009).

The ‘wide’ block orientation used in condition 4 created a unique situation because unlike all other conditions, the entire foot could not fit on the block without turning perpendicular to the direction of travel. Participants were instructed to step naturally and comfortably but were not told how to step on the wide block. Pilot testing identified fore–foot, mid–foot, and rear–foot strikes as potential strategies. It was expected that a fore–foot approach would intuitively be adopted by participants because the ball of the foot is mechanically the most compliant. The data plotted in figure 3.7 are from the marker located on the dorsum of foot above the head of the fifth metatarsal. It is evident from the cluster of points between 0 and 50 mm that a fore–foot strike was employed almost exclusively with some participants trending slightly more toward a mid–foot strike strategy.

As hypothesized, the axis to axis distribution of variability observed in condition 3 was essentially interchanged by rotating the block to the wide orientation in condition 4. Not surprisingly, the least amount of anterior–posterior variability was observed in this condition (figure 3.11, panel 4). As was the case in condition 3, the interesting result is the expansion of medial–lateral variability. Although, as demonstrated by the other conditions, participants were clearly able to complete repeated trials within a narrow area of foot placement without slowing down, they exhibited a large degree of medial–lateral variability. The variability was nearly equivalent to that measured in condition 1 where there were no constraints. Participants used a large area of the wide block even though it was not necessary to do so. Again, by allowing the environment to dictate available footholds instead of aiming for an ideal point, the locomotor control system maximizes probability of successful step while minimizing control effort.

When applied to the findings of the present study, the concept of a 'locomotor affordance manifold' provides an elegant explanation. The concept is based upon the original uncontrolled manifold hypothesis which requires a state space of variables in which to function (Scholz et al., 1999). Because the uncontrolled manifold concept can be applied in a variety of domains, it is possible that the variable comprising state space, and thus which is controlled during adaptive locomotion tasks, is not simply end–effector position, but an extension that incorporates the effector–environment interaction. The state space is thus a set of affordances. The controlled subspace, or locomotor affordance manifold would correspond to the walking surface and provide an informational framework from which movements could be executed.

During unconstrained gait on level ground, each point on the ground offers a near equivalent degree of 'effectiveness' if it were to be used as a foot placement. The uniformity of the affordance for locomotion permits minimum intervention or control and results in the spatially distributed footfall variability observed in unconstrained conditions. Introduction of effective footholds into rough terrain, such as the target blocks, creates attractor states in the locomotor affordance manifold. The complex interaction of the movement elements fluctuate and evolve towards the stable patterns of attractor states thus increasing the probability of a movement that closely approximates the attractor state. Because the state space is tied to physical space, peaks in the landscape of the probability field begin to resemble the target blocks. With repeated trials, these probabilities become evident in the variability of foot position. Instead of displaying acute maxima with smooth slopes, a stepping stone, for example, may have a more broad plateau shaped maximum with sharply truncated, near vertical slopes. This results in the observed congruence between footfall variability and the shape of the affordance.

Total Variability of Right Foot on Target

Because it appears that the locomotor control system is operating at least somewhat independently in the two axes, ‘total variability’ was calculated in order to gain a more holistic perspective of footfall variability. Total variability was calculated by multiplying the standard deviation of footfall position from each axis. The resulting data are presented in figure 3.10 where the effect of including targets is prominent in the panels for the second left and right steps. For the right foot, the inclusion of flat targets in condition 2 resulted in a statistically significant, approximately 70%, reduction in total variability from the unconstrained walkway present in condition 1.

A smaller but still significant difference was present between the long and wide blocks of conditions 3 and 4 respectively. Despite having the same available surface area, more variability was present in condition 4. This can be attributed to the stronger transverse axis constraint present in the long orientation. When the long axis of the foot was parallel with the long axis of the block in condition 3, a shorter distance is available before medial–lateral deviations result in the centre of pressure crossing the edge of the support surface. In contrast, the perpendicular orientation of the long axes of the block and foot in condition 4 created a weaker constraint. A larger magnitude of deviation in the anterior–posterior axis was tolerable before the centre of pressure left the support surface. A similar difference in total variability was found between conditions 5 and 6 where the physical constraint of the raised square in condition 5 resulted in significantly less variability than the purely visual constraint of the flat square.

Gibson (1979) described an optical flow field from which affordances for action were directly perceived. He subsequently argued that movement control arose from the animal–environment system rather than from the brain. This approach is attractive because firstly, it is compatible with the modern understanding of biological systems as complex dynamical systems and secondly, it does not rely upon the notion of a centrally programmed controller which is subject to an ‘infinite regress’ of explanatory power. If Gibson’s premise is accepted and the interaction between environmental features and the individual functions as the determinant of locomotor behaviour over rough terrain, it follows that the system must function probabilistically rather than deterministically in order to cope to with the uncertainties inherent to both perceptual processes and open environments. Warren and Fajen (2004) modelled the behavioural dynamics of navigation through cluttered environments as a dynamical system in which the state space represented physical location. The set of differential equations determined travel paths through groupings of obstacles, represented as repellors in state space, to a goal feature, represented as an attractor. In their model, Warren and Fajen included time–to–contact as a mechanism by which nearer objects are given greater weight in the differential equations that collectively determine behaviour. The success of this model in predicting human behaviour opens the possibility for an extension of this approach to other aspects of adaptive locomotion such as foot placement selection.

Areas of the environment with a high degree of foothold effectiveness would correspond to attractor states in the locomotor affordance manifold. Conversely, areas affording little capacity as footholds would correspond to neutral state space and those which may be hazardous or otherwise detrimental would correspond to repellors in the state space. The strength of an attractor would translate to a proportionate probability of foot placement at that location.

Intuitively, the area immediately in front of the individual would be most defined with clear peaks and troughs of foot placement probability. The strength of attractors and repellors would increase as proximity and thus information increase. The probability landscape would therefor collapse into distinct peaks and troughs as time–to–contact decreases. Even extremely well defined constraints, such as a long jump take–off board, would not become distinct enough to act upon until time–to–contact reached a sufficiently low threshold.

During unconstrained locomotion when the essential requirements for foot placement are satisfied nearly everywhere, factors such as energy efficiency may begin to dictate attractor states in the locomotor affordance manifold. There would also likely be a critical point at which the system recognizes increasingly large features as elements that cannot function as locomotor affordances and thus switches to a different behaviour such as stair climbing.

Future Directions

The wide block present in condition 4 raises some important considerations. In this case the consistent use of a fore–foot strike permitted an interpretation of results parallel to those of condition 3; however, the result would have been different had participants used different foot strike strategies. In this instance the interaction between the target block and the participants created a relatively uniform locomotor affordance; however, a great deal of room exists for work to be done in this regard. As the product of an interaction between environment and individual, many variables influence what features of an environment may be used as footholds. In particular, the effect of variable weight bearing properties of either the shod or unshod foot such as stiffness, compliance, load bearing surface area, and pressure sensitivity needs to be investigated. The specific relation of foot dimensions relative to the surface dimensions also needs to be explored with a more detailed model of the foot and incremental target block changes.

Part of the difficulty in quantitatively assessing geometric congruence is that medial–lateral variability may not be directly comparable to anterior–posterior variability. Future work could be directed toward the possibility of scaling or normalizing factors that account for momentum, range of motion, and direction of travel.

The concept of synergies and their associated geometric analyses based on the uncontrolled manifold hypothesis are a promising avenue for future research into the rough terrain problem. However, in order to apply the UCM approach, an a priori hypothesis about candidate control variables must be made. For example, a candidate variable of end effector position would require a dynamic kinematic model of the entire kinetic chain as well as a goal position. An uncontrolled manifold would then consist of all the joint configurations that produce the same end effector position, which is what this particular synergy would stabilize. Control would be exerted by specifying a desired position and allowing the established lower level relations between elements of the synergy to implement the details. This ‘effectiveness’ is open to definition but would need to be a composite function incorporating all the determinants of effective locomotion outlined by Patla (1991b). Ultimately all the mechanical properties of the individual would need to be incorporated into the model; from effector–surface interaction properties, to leg swing dynamics, to whole body momentum. This incorporation could occur as a set of differential equations representing a singular synergy or as a series of separate synergies nested hierarchically. Either way, the resulting ‘rough terrain synergy’ would act to stabilize a specific value for each step within a state space that corresponds to the physical environment.

The viability of this model is contingent upon empirical answers to several unknowns; the most significant of which is what specific factors are included in the composite ‘effectiveness’ function. As a first course of action, a geometric variability analysis of leg swing kinematics could confirm if and under what circumstances a rough terrain synergy is employed.

Conclusion

The purpose of this study was to investigate the relationship between geometric features of the walking surface and spatial patterns of movement variability. Observation of spatial footfall variability patterns that were congruent with the shape of the stepping blocks provided evidence in support of the general hypothesis. Expansion of footfall variability occurred along axes in which area was available even though data from complementary conditions demonstrated locomotion was equally efficacious with a smaller constraint. This was interpreted as evidence of a strategy that maximizes the probability of a successful foot placement and minimizes the need for intervention by stabilizing movement within boundary conditions rather than optimizing movement to a point.

The present findings are consistent with the locomotor pointing and obstacle avoidance literature. Analysis of foot swing velocities demonstrated that stepping from the walkway surface onto an elevated target resulted in faster leg swing velocities. The phenomenon was interpreted as indicative of a leg elevation strategy employed in any instance of an obstacle in the travel path, regardless of whether it will be avoided or used as a foothold. Although our capacity to draw further comparison is limited by the differences in protocol and paradigm, this apparently conserved mechanism and absence of otherwise contradictory findings suggests the grouping of obstacle avoidance, locomotor pointing, and stepping stone studies as components of the rough terrain problem is justified. Future work should incorporate more detailed analyses of gaze behaviour and leg swing kinematics to strengthen the interpretation of results.

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Appendices

Appendix A: Left Foot Correlation Table

Table A.1 Pearson product moment correlations between anterior–posterior position and medial–lateral position for left foot on target.
(*p < 0.05, **p < 0.01)

Participant Number	Condition					
	C1	C2	C3	C4	C5	C6
1	-0.173	-0.194	-0.134	-0.157	0.037	0.040
2	$-.522^{**}$	0.196	-0.108	-0.063	-0.075	0.055
3	-0.116	$-.529^{**}$	-0.075	-0.186	0.054	$-.532^{**}$
4	0.114	0.205	$.459^{*}$	-0.206	-0.035	-0.055
5	-0.211	-0.080	-0.250	-0.244	-0.233	-0.070
6	0.044	0.092	0.303	-0.014	-0.186	-0.177
7	0.179	$.503^{*}$	-0.083	-0.262	-0.173	-0.096
8	0.231	-0.207	0.186	$-.454^{*}$	0.020	0.032
9	0.091	-0.177	0.259	-0.233	0.204	0.081
10	0.023	$.588^{**}$	$.453^{*}$	0.152	-0.069	0.146
11	0.263	0.172	-0.123	-0.150	0.214	0.044
12	0.057	-0.080	0.245	-0.185	-0.119	-0.319

Appendix B: Right Foot Correlation Table

Table A.2 Pearson product moment correlations between anterior–posterior position and medial–lateral position for right foot on target.
(*$p < 0.05$, **$p < 0.01$)

Participant Number	Condition					
	C1	C2	C3	C4	C5	C6
1	-0.322	-0.075	-0.281	-0.084	$.455^{*}$	-0.300
2	$-.409^{*}$	0.231	$-.516^{**}$	-0.013	0.185	-0.358
3	-0.306	-0.015	0.011	0.102	-0.306	-0.179
4	$.455^{*}$	0.196	0.119	0.170	-0.186	-0.243
5	-0.161	-0.327	0.075	0.054	-0.068	-0.360
6	-0.091	-0.069	0.005	0.035	0.085	-0.040
7	0.128	$-.540^{**}$	-0.353	-0.001	-0.030	0.189
8	0.091	-0.151	-0.201	-0.077	0.111	0.046
9	-0.020	-0.112	0.192	-0.335	0.131	$-.453^{*}$
10	-0.307	-0.044	-0.107	-0.385	-0.199	0.242
11	0.030	-0.117	$-.439^{*}$	-0.002	-0.302	-0.231
12	-0.192	-0.236	-0.124	0.329	-0.182	-0.278