I am the author of the thesis entitled

INFORMATION-BASED REGULATION OF HIGH-VELOCITY FOOT-
TARGETING TASKS

Submitted for the degree of

DOCTOR OF PHILOSOPHY

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INFORMATION-BASED REGULATION OF
HIGH-VELOCITY FOOT-TARGETING
TASKS

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Submitted in fulfilment of the requirements for
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June 2001
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CANDIDATE DECLARATION

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*Information-Based Regulation of High-Velocity Foot-Targeting Tasks*,

submitted for the degree of:

*Doctor of Philosophy (Human Movement)*.

I certify that the thesis is the result of my own research, except where otherwise acknowledged, and this thesis in whole or in part has not been submitted for an award, including a higher degree, to any other university or institution. This thesis may be made available for consultation, loan and limited copying in accordance with the Copyright Act 1968.

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Abstract
Judging time-to-contact with a target is an important criterion for avoiding harm in everyday walking and running tasks, and maximizing performance in high-velocity sporting tasks. The information-based regulation of step length and duration during target-directed locomotion was examined in relation to gait mode, approach velocity, target task, expertise, and sporting performance during a series of four experiments. The first three experiments examined novice performers (Each n=12, 6 males, 6 females), whilst the last experiment examined expert gymnasts (n=5). Two reference strips with alternating 50cm black and white intervals were placed on either side of the approach strip for all of the experiments. One 50Hz-panning video camera filmed the approach from an elevated position. In Experiment 4, two stationary 250Hz cameras filmed the post-flight performance of the gymnastic vaults and, in addition, two qualified judges provided a performance score for each vaulting trial. The panning video footage in each experiment was digitized to deduce the gait characteristics. In Experiment 4, the high-speed video footage was analyzed threedimensionally to obtain the performance measures such as post-flight height. The utilization of visual stimulus in target-directed locomotion is affected by the observer’s state of motion as characterized by the mode of locomotion and also often the speed of locomotion. In addition, experience plays an important role in the capacity of the observer to utilize visual stimulus to control the muscular action of locomotion when either maintaining or adjusting the step mechanics. The characteristics of the terrain and the target also affect the observer’s movement. Visual regulation of step length decreases at higher approach speeds in novice performers, where as expert performers are capable of increasing visual regulation at higher approach speeds. Conservatism in final foot placement by female participants accounts for the observed increase in distance from the critical boundary of the
obstacle relative to toe placement. Behavioural effects of gender thus affect the control of final foot placement in obstacle-directed locomotion. The visual control of braking in target-directed locomotion is described by a tau-dot of −0.54. When tau-dot is below −0.54 a hard collision with the obstacle will occur, however, when tau-dot is above −0.54, a soft collision with the target will occur. It is suggested that the tau-dot margin defining the control of braking reveals the braking capacity of the system. In the target-directed locomotion examined a tau-dot greater than −0.70 would possibly exceed the braking capacity of the system, thus, leading to injury if performed. The approach towards the take-off board and vaulting horse in gymnastics is an example of target-directed locomotion in sport. Increased visual regulation of the timing and length of each step is a requirement for a fast running approach, a fundamental building block for the execution of complex vaults in gymnastics. The successful performance of complex vaults in gymnastics leads towards a higher judge’s score. Future research suggestions include an investigation of visual regulation of step length in curved target-directed locomotion.
Chapter 1

General Introduction
Many contingencies within the everyday environment require accurate foot placement and, as a consequence, the action of visually regulating locomotion towards a target is characteristic of a broad class of gait tasks. Stepping on or off a footpath, stepping into a shower, and climbing stairs are real-world gait tasks that impose foot-target constraints. Similarly many sports present challenges to foot targeting, such as the approach to the take-off board in long jumping and gymnastics vault. Bradshaw & Sparrow (2000) have unequivocally shown that approach speed decreases when a target impedes an individual’s path. Decreasing approach speed enables the observer to adjust step length to negotiate a target.

Adjustments to step length and duration enables optimum foot placement to negotiate a target. Humans tend to be very confident when negotiating a cluttered environment that is highly familiar, but less confident in unfamiliar circumstances. Negotiating rocks to cross a stream when bush walking or clearing hurdles whilst running are foot-targeting tasks that are unfamiliar to the majority. A cautious approach is usually adopted when the targeting task and environment is unknown, with the avoidance of injury a priority. Task experience is an example of a mediating variable, which affects our interaction with targets in the immediate environment. Gender, body size, age, gait mode, and leg strength can also be considered mediating variables (Tyldesley & Whiting, 1975; Wrisberg & Mead, 1983; van der Meer, 1997) affecting the visual regulation of target-directed walking and running.

**The Ecological Approach to the Guidance of Locomotion**

Visual regulation is essential to the adjustment of step length and duration to negotiate a target in the environment. Humans adjust step length and duration quickly and appropriately to accommodate targets in their surroundings. A growing literature
(e.g. Lee, 1976; Tresilian, 1991) suggests that to accomplish this humans use the higher order optical information of time to contact to guide movement rather than lower order information where image size, distance, and velocity are utilised to guide the action (Schiff & Oldak, 1990). From a direct perception perspective, the environment composes a collection of “affordances” for action, which the animal can detect (Gibson, 1958). The affordance of a target within the environment, either a one-dimensional surface or a three-dimensional object, provides the event for action, with light acting as the carrier of information about the surrounding environment of surfaces.

![Diagram](Figure 1.1. The optic array; the projection of rays due to the reflection of light from surfaces, which converge at the eye.

The Optic Array During Human Locomotion

When walking or running towards a target, the passage of light received at the eye from the target’s surface gives rise to an optic flow field (Figure 1.1). The observer can immediately sense change and the gradient of change from successive observations during movement through the environment towards a target, such as changes in position and time to arrival (Gibson, 1958, Lee, 1980). The observer must perceive surface characteristics (targets) in the immediate environment to initiate the walking and running action, and the observer is compelled to adjust step length and duration to accommodate the target in an optimum manner.
To guide foot placement during locomotion towards a target, he or she must keep the centre of flow (locomotor flow line) of the optic array towards the target (Gibson, 1958; Lee, 1980). The centre of flow of the optic array during locomotion towards a target shifts corresponding to the movement of the head and body. Keeping the target in the centre of the optic flow is important when trying to maximize approach speed, such as in long jumping, and also when approaching a thin target such as a wooden plank or a gymnastics beam.

Aside from utilising optic flow to guide the direction of travel when walking or running towards a looming target, humans must also time the approach consistent with the type of collision with the target. There are two types of collisions with a target, a hard impact where the observer collides with the target and continues to move (runs through the target), or a soft impact where the observer stops at the target.

**Time to Contact Information in Target-Directed Movement**

Time to contact information about the impending collision of the observer with the target during locomotion is perceived from the visual angle of the eye with the target during the forward movement. The visual angle ($\Theta$) increases geometrically during forward motion, such that the inverse rate of optical expansion yields time to contact information (Lee, 1976). The optical quantity of time to contact, known as tau ($\tau$), is calculated as follows:

$$\tau = \frac{\Theta}{\dot{\Theta}} = T_c$$

(Optical Tau)

In addition to the method for calculating optical tau, when examining target-directed locomotion, tau can also be calculated from environmental measures consisting of the observers walking or running velocity, and his or her distance from the target at a specific time, by calculating the following ratio (Lee, 1974):
\[ T_c = \text{Distance from the target} \quad \text{(Environmental Tau)} \]

Approach velocity

The perception of time to contact during each step enables accurate timing of the approach movement towards the looming target (Patla, 1989; Warren & Yaffe, 1989). The observer can then utilise this information to judge whether further changes to step length and duration are needed to control the approach and final foot placement when negotiating the target. When sprinting to a narrow target, for example, the observer must regulate approach velocity and step length in order to accurately place the foot within the boundaries of the target (Bradshaw & Sparrow, 2000).

Underlying an observers ability to obtain time to contact information (tau) with a target and control step length and duration, is when the observer requires this visual information during the task. A second important consideration for the current study, therefore, was also when the observer utilizes vision.

**The Use of Vision in Human Gait Tasks**

When walking or running through the environment towards a stationary target, humans are capable of adjusting step length and duration to accommodate a target with the required action, such as stepping on or over. The capacity to perceive information comprising the target characteristics from the optical field governs the control of the approach kinematics in locomotion towards a target. In addition, the time during the approach when information is needed by the observer to control the movement towards the target, further affects the approach kinematics.

Vision during foot-targeting tasks can be categorised into the types of information available to the observer. Global information gives the observer self-motion perception about his/her direction, speed and time to contact with a target position, thus guiding the observer towards the goal. Tau estimates in this case are
made from the radial (locomotor line) outflow during the observer's movement (Tresilian, 1990). Closer to the target, local visual information is provided in the form of object motion perception (Laurent, 1991). When the observer is closer to the target, specific target characteristics such as length can be perceived from the expansion rate of the object. A three-phase kinematic profile may, therefore, govern the regulation of target-directed locomotion, consisting of an accelerative phase, a global visual control phase, and a local visual control phase. To competently examine the effects of targets and mediating variables on the approach characteristics in target-directed it was, therefore, necessary to identify the global and local visual control phases.

![Graph showing visual control onset](image)

**Figure 1.2.** The identification of visual control onset from the consistency of foot placement (standard deviations) for the approach towards a target across several observations. Visual control onset is identified as occurring at the peak standard deviation of the footfall positions for the entire approach, provided that the standard deviations then begin to decrease systematically.

In target-directed locomotion (e.g. Lee, Lishman & Thomson, 1982; Berg, Wade & Greer, 1994; Abendroth-Smith, 1996), the emergence of visual control after
the accelerative phase has been identified from the consistency of foot placement during the approach. The consistency of foot placement is obtained from the standard deviation (variability) of the footfall positions, which are calculated for each footfall position relative to the target, for the entire approach across several observations (trials). Visual control onset, the point at which visual regulation of step length and duration emerges, is identified as occurring at the peak standard deviation of the footfall positions for the entire approach, provided that the standard deviations then begin to decrease systematically (Berg, Wade, & Greer, 1994) (Figure 1.2).

The decrease in the standard deviations of foot placement represents visual control of foot placement with respect to the position of the target. The type of visual regulation, global or local, that emerges in target-directed locomotion through this method was not identified by Lee, Lishman, and Thomson (1992), Berg, Wade, and Greer (1994), or Abendroth-Smith (1996). It was suggested that the peak of the standard deviations for footfall position in target-directed locomotion identifies when global visual control emerges during the approach. To identify the local visual control phase it was, therefore, necessary to determine when target characteristics such as length can be perceived.

**Target Perception**

During the local visual control phase, perceptual information is gained from the expansion rate of the target on the retina. The utilisation of the optic flow field through the expansion of the target on the retina to gain time to contact information and the characteristics of the target occurs when the target perception threshold has been reached and, therefore, can be identified in target-directed locomotion. The perceptual threshold for perceiving changes in angular velocity (ω) due to the optic
flow field generated between the movement of the observer and the surface of the target is approximately $\frac{1}{12}$ deg/s (Lee, 1976). Angular velocity for the perception of target characteristics in locomotion is:

$$\dot{\omega}(t) = \frac{wZ}{Z(t)^2}$$

where $w$ is the length of the target, $Z$ is the distance, and $\dot{Z}$ is the approach velocity at time $t$. At certain distances prior to the target perception threshold, that is, during global visual control, the target may be perceived to be so small that it does not provide any relevant information to guide the timing of the braking action to accommodate the characteristics of the target, thus guiding final foot placement to negotiate the target (Laurent, 1991). It was expected, therefore, that timing of the global and local visual control phases in the approach kinematics would reveal the magnitude of adjustment required to accommodate the characteristics of the target.

**Visual Regulation and Task Constraint**

From the direct perception approach, information is considered specific to events and actions, this means that the step number at which visual regulation is initiated should be a function of the amount of adjustment required to complete the task (Montagne et al, 1996). Understanding the control of target-directed locomotion requires us first to identify the information required to control target-directed locomotion. In target-directed locomotion, therefore, it was necessary to identify the effects of target characteristics such the number of boundaries defining the target, on the walking or running action of the approach and final foot placement. When there is no direct consequence of movement error such as, for example, no risk of tripping or falling if final foot-placement is not placed within the boundaries of a target, approach performance increases whilst the interceptive action performance decreases. In the
case of a traditional double-boundary target aiming tasks in locomotion, the speed/accuracy trade-off describes the phenomenon where approach speed slows when foot placement is highly constrained by a narrow target (Bradshaw & Sparrow, 2000).

**Summary**

The control of locomotion and the perception of targets (affordances) have not been considered together, that is, the control of locomotion and time-to-contact judgements has previously been considered as generic image properties, with only an

**Experiment 1: 10m Walk, Jog, Run**

Double Boundary (Target)  Single Boundary-Toe  Single Boundary-Heel

**Experiment 2: 10m Walk, Jog, Run**

Rod  Platform (Box)  Gymnastics Take-Off Board

**Experiment 3: 10m Run-Hard/Soft Impact**

Target (Shoe Length + 5/10/15 cm)

**Experiment 4: Run-21.51m average approach**

Take-Off Board  Take-Off Board & Vaulting Horse

Figure 1.3: The targeting tasks examined and to be reported from the current study.
indirect relation to the composition of surfaces (Nakayama, 1994). The current study will address whether locomotion is controlled within a world of perceived surfaces, or whether primitive processes of motor control exists that might be driven by generic image information alone. The observer’s ability to control locomotion towards a target, whether the target is treated as a generic image or a specific image, may also be governed by a number of mediating variables. Task experience is an example of a mediating variable that affects the observer’s ability to control foot-placement with a target but researchers have predominantly overlooked the exact effect on the approach kinematics and step pattern.

In the current study the information-based approach for the control of the step length and duration in foot-targeting tasks will be adopted in order to investigate the effect of different targeting tasks and mediating variables such as mode of locomotion, gender, and experience on the action of walking and running, as shown in Figure 1.3. Experiments will be reported on simulated (laboratory-based) target-directed locomotion of male and female novice performers to examine the effect of affordances, across a range of approach velocities (walking, jogging, sprinting) (Chapters 3, and 4). Furthermore, a highly challenging real-skill of target-directed locomotion from women’s gymnastics will be examined and reported, extending the investigation of information comprising the effects of target characteristics and mediating variables on step length regulation and final foot placement (Chapter 5). First, however, a more in-depth discussion of the empirical and theoretical issues is presented, drawing on the literature concerning the speed/accuracy constraints in foot targeting, direct perception, and the visual control of locomotion.
Chapter 2

Literature Review
Understanding the control of step length and duration when walking or running towards single stationary targets requires the identification of the affordances (target characteristics) and the mediating variables (e.g. gender, experience). Thus, to evaluate the kinematics and the step pattern during locomotion towards a target, the information, comprising the specific affordances and mediating variables, must be identified.

**Affordances in Target-Directed Locomotion**

Affordances in simulated (lab-based) walking and running situations consists of the stationary surface, known as the target, and the requirement to either stop at the target (hard impact) or negotiate the target and continue to move (hard impact). In the real-world, affordances consist of the stationary target and, also, often a second surface that directs the observer on how to interact with the stationary target. For example, when walking to a road-side, an oncoming automobile would change the interaction with the stationary target to a soft impact, that is, the observer would be compelled to stop. Alternatively, in long jumping the affordances encountered, the take-off board and large sand pit, do not compel the observer to stop at the target but to strike it and continue moving. To examine the affordances present in direct approaches towards targets, major consideration concerns the stationary target characteristics but also whether the collision with the target is either hard or soft.

Whilst there is an extensive literature on walking or running towards a target (e.g. Lee, Lishman & Thomson, 1982; Hay, 1988; Berg, Wade & Greer, 1994), only one study has examined the information-based control of running to a target (Bradshaw & Sparrow, 2000). The affordances in Bradshaw and Sparrow’s (2000) study were double-boundary targets of different lengths (defined by two parallel
lines), for both hard and soft impact collisions. There are few other examples in the literature on the affordances in aiming towards a target, aside from investigations utilising small and large targets with a soft impact (e.g. Bardy & Laurent, 1991). The speed/accuracy constraints derived from target length manipulations in foot targeting, provide a basis for examination of the affordances and therefore will be reviewed first.

**Speed/Accuracy Constraints in Foot-Targeting Tasks**

A fundamental principle of motor control in humans is that as movement speed increases accuracy decreases. In 1954 Fitts first described formally the relationship between target width, movement amplitude (distance), and movement speed.

![Graph](image)

**Figure 2.1.** The typical Fitts’ Law relationship (adapted from Fitts, 1954) with the target widths indicated in the right panel. A linear relationship characterises the speed/accuracy trade-off, where movement time increases when the targeting task difficulty increases.
time, where an increase in target width led to a systematic decrease in movement time. The function reflecting the speed/accuracy trade-off where speed and accuracy are balanced within the constraints of the task is linear (Figure 2.1). The linear movement time and accuracy relationship was originally formulated by Fitts (1954) as $ID = \log_2(2A/W)$ where ID is the index of difficulty, A is the amplitude or distance to the target, and W is the target width. The speed/accuracy trade-off principle has been demonstrated in rapid aiming movements and reaction time (Fitts & Peterson, 1964). More recently, a speed/accuracy trade-off has been found in target-directed running where the steps shortened in length to accommodate a narrow target, resulting in decreased approach velocity (Bradshaw & Sparrow, 2000).

**Target Width, Impact, and Action in Running**

Bradshaw and Sparrow (2000) indicated that target length was the main determinant of task difficulty in running, as opposed to a combination of approach distance and target length, consistent with Fitts’ Law. Furthermore, the inclusion of probe width (P) in the calculations of task difficulty, a correction to the formula for rapid aiming tasks postulated by Hoffman and Sheikh (1991) as $ID = \log_2(2A/W+P)$, was not advantageous in describing the speed/accuracy relationship for the task of running to a target. Bradshaw (1997) suggested that the additional constraint of a longer foot (large probe width), is offset by the participant also having a longer step length and running faster.

The constraint of a double-boundary target due to its anterior-posterior extent (length) that will require visual regulation and, in addition, a speed/accuracy mechanism is limited in range for whole-body direct approaches (Bradshaw & Sparrow, 2000). A double-boundary target of the same length as the observers normal
step length presents no constraint to the observer and can be accommodated into the step length pattern without visual regulation of step placement. A range of longer targets, representing 60-80% of step length for example, may require visual regulation of step length, but would not cause a speed/accuracy trade-off. Thus, the smaller target in the aforementioned range would affect approach speed at the same magnitude as the larger target.

In target-directed walking it has been suggested that target lengths greater than 30cm would not induce a speed/accuracy trade-off (Drury & Woolley, 1995). An error margin is generally associated with human movement, and as the average shoe length of humans is close to 30cm, Drury and Woolley (1995) have underestimated the upper limit for constraint in target length for walking. It was suggested that an upper limit for target length constraint necessary to induce visual regulation and a speed/accuracy trade-off mechanism in walking is closer to 35cm. When running and striking the target accurately in a hard impact, the spatial limit for target constraint to induce a speed/accuracy trade-off is 57cm (Bradshaw & Sparrow, 2000). In soft impacts with a target when running, the cut-off point with respect to target length is 43cm. In experiment 3 the effect of target length on the approach kinematics and step length and duration adjustments was examined for hard and soft impacts. In experiment 3, therefore, target length was manipulated below 43cm.

To maximize speed in an approach towards a target for hard and soft impacts, the target length should be greater than 43-57cm. The stationary target in gymnastics vaulting, the take-off board, is an example of a real-world target that does not induce speed/accuracy constraint (Figure 2.2). The area providing the greatest return of potential energy is the upper half of the 1.20m gymnastics take-off board. The effective target length of the gymnastics take-off board therefore is 60cm. Gymnasts
approach the take-off board whilst running with step lengths greater than 60cm (Meeuswen & Magill, 1987). The running approach towards the gymnastics take-off board was examined for novice and expert performers in Experiments 2 and 4. Visual regulation of the approach was expected to be evident in this target-directed locomotion, however, it was expected that a speed/accuracy trade-off would not govern the control of the approach.

![Image of gymnastics take-off board]

**Figure 2.2**: The 1.20m gymnastics take-off board. Typically gymnasts aim for the upper half of the take-off board as this section provides the greatest return of potential energy.

The length of a double-boundary target either in a simulated setting such as a lab-based experiment or in the real-world such as the take-off board in gymnastics affects the gait characteristics of the approach, reflected in the overall speed of locomotion. Aside from the actual length of the target are the critical boundaries that define the target. A double-boundary target comprises a forward boundary governing the placement of the toe and a rear boundary guiding the placement of the heel. Which boundary of a double-boundary target is principally utilised in the guidance of foot
placement has not been examined in the literature, neither has the influence of each boundary on approach speed and the step characteristics such as length. To examine the affordance of a double-boundary target it was necessary to first examine how the critical boundaries of the target affect the action, particularly the accuracy of foot placement (Experiment 1). It was expected that the forward boundary of the double-boundary target would be the principal guide for foot placement, but that foot placement accuracy would decrease when either boundary was not present. In this study targets more like real skills, such as a horizontal rod (similar to a hurdle), were used to examine target composition issues in gait tasks, but in a controlled setting (Experiment 2). Finally, an experiment on gymnastics vaulting enabled the examination of target-directed locomotion to extend to a real-world gait task, where a high approach velocity and accurate foot placement is a fundamental requirement for performance success (Bruggemann & Nissenen, 1987; Krug, Knoll & Zocher, 1998). Through a series of four experiments on task difficulty (affordances), the effect on the resulting action, that is, the final approach speed, was examined.

Kinematics of Double-Boundary-Foot Targeting

The empirical relationship between approach speed and task difficulty is revealed in the kinematics for the approach. The kinematic characteristics of the approach in target-directed locomotion has been shown to consist of two phases (Bradshaw & Sparrow, 2000), an accelerative phase during which the participant reaches the necessary approach speed for the gait task, and a visual control phase where the participant adjusts the timing and length of each step to accommodate the target. The visual control phase was hypothesised to contain global and local components. The target constrains approach speed predominantly during the global
and local visual control phase, when corrections are made to step length and duration to enable optimum foot placement to negotiate the target (Bradshaw & Sparrow, 2000). The magnitude of adjustment, reflected in the movement kinematics, is directly related to the affordances prescribing the difficulty of the task, such as the length of the target and task experience.

![Graph](image-url)

**Figure 2.3.** The acceleration/time profile for the unconstrained (sprint) and target-directed running when either contacting the target and continuing to run (hard impact) (a), or stopping within the target (soft impact) (b) for an 8m approach distance (from Bradshaw, 1997). The difficulty of each task (ID) was defined by Fitts’ Law, a combination of the target length and approach distance.
The movement kinematics of target-directed running was also examined by Bradshaw (1997) for both hard and soft impacts with the target (Figure 2.3). During the first phase of target-directed locomotion there is a period of initial rapid acceleration in both tasks, consistent with the task of initiating the forward momentum of locomotion from a stationary starting position. In the hard impact task, the visual control phase is characterised by a second smaller period of acceleration. This smaller period of acceleration during the visual control phase could be due to the target perception threshold being reached, allowing the timing and length of the steps to be adjusted accurately to allow the final footfall position to occur within the boundaries of the target. In the soft impact task, the visual control phase is characterised by deceleration.

In this earlier study on target-directed running (Bradshaw, 1997) the velocity and acceleration patterns for target constrained running were compared to unconstrained running (Figure 2.3). Differences in the velocity and acceleration patterns were found for the hard impact task between the unconstrained and target-constrained approaches for the entire approach. In the soft impact task, however, no significant differences between the velocity and acceleration profiles during the accelerative phase were found between the unconstrained and constrained conditions. The kinematic profile for soft impact target-directed locomotion suggests that the initial phase is ballistic, where the participant accelerates to reach the necessary speed of locomotion.

The decrement in running velocity for a double-boundary target ranged from approximately 2-4% in hard impact tasks and 17-20% in soft impact tasks (Bradshaw, 1997). The constraints on approach velocity imposed by a double-boundary target can have a detrimental effect on performance in sport. Bruggemann (1987), for example,
showed that a higher approach velocity in gymnastics vault resulted in a superior performance as measured by qualified judges (Figure 2.4). In gymnastics vaulting, the affordances encountered, the take-off board and vaulting horse do not compel an expert observer to stop, whereas a novice performer might stop. This interestingly highlights an effect of mediating variables such as task experience.

![Graph](image)

Figure 2.4. The relationship between level of performance and approach velocity in gymnastics vaulting (adapted from Bruggemann, 1987).

**Mediating Variables in Target-Directed Locomotion**

The ability of the observer to visually regulate step length and duration towards a target may vary as a function of mediating variables such as developmental age, gender, and task experience (Abernethy & Burgess-Limerick, 1992). Mediating variables such as gender can effect movement performance and, therefore, must be detected and evaluated when examining the information-based actions of target-directed walking and running. In experiment 4, the real-world task of gymnastic vaulting was examined utilising expert performers. The performers were aged 13-15 years. As the task itself was predictable due to the stationary position of the targets, timing ability is well developed by this age (Dorfman, 1977; van der Meer, 1997). Developmental age as a mediating variable was, therefore, not examined in the
current study. Aside from task experience, however, gender as a mediating variable was examined in experiments 1, 2, and 3.

**Gender**

Wrisberg and Mead (1983) stated that gender differences in coincident timing skill, a 43cm arm movement towards a target coincident with the end of a light sequence, will be only be different if the required movement involves the coordination of large muscle groups. Gender could be a mediating variable in locomotion timing tasks as walking and running involves the large muscle groups of the legs, trunk, and arms. Richard et al (1995), however, revealed that gender does not affect walking speed when unconstrained by an obstacle. Females have a shorter step length (1.3m) when compared to males (1.5m), but have a higher step frequency (females: 1.93 steps/s, males: 1.75 steps/s) (Richard et al, 1995). It therefore appears unlikely that the timing of target-directed gait tasks would be affected by the gender of the participant.

A second gender difference in spatiotemporal judgements in aiming movements that is described in the literature is behavioural. Schiff and Oldak (1990) suggested that conservatism could account for the gender differences they found between male and female observers judging the time of arrival of pedestrians and automobiles. Females tended to allow a safety-margin for error in time-to-contact judgements. In walking, Chen et al (1991) examined the kinematic characteristics of stepping over a 2.5cm-high obstacle, finding that the lead heel clearance over the obstacle for females was 6.82cm, 1.09cm higher than the male participants. Chen et al’s (1991) findings could possibly be explained by the behavioural gender effect where females allow a safety-margin for error. There are numerous studies of timing performance, however, that have failed to find evidence of gender differences (e.g.
Haywood, 1980; Isaacs, 1983). In the current experiments it was hypothesised that behavioural gender effects would be found in locomotion towards the target. Specifically, female participants were expected to place their foot further from the critical boundary of the target, thus allowing a safety-margin for perceptual judgement error. Experience, however, was also expected to be a mediating factor in timing walking or running to a target.

Task Experience

Superior spatiotemporal judgements, timing skills, are an important component of expert performance in target-directed walking and running tasks (Abernethy & Burgess-Limerick, 1992). The experienced observer is capable of moving precisely within smaller periods of time than a novice observer. Furthermore, the experienced observer is capable of reproducing ballistic movement sections with ease (Tyldesley & Whiting, 1975), such as during the accelerative phase when running and stopping at a stationary target (Bradshaw, 1997). Cavallo and Laurent (1988) demonstrated that experienced drivers are capable of more accurate time to contact judgements than novice drivers. Also of relevance to the current study, is the study by Scott et al (1997) of novice performers in long jumping. In addition to the identification of visual control onset from the standard deviations in foot placement for the entire approach, is an assessment of the approach variability by calculating the mean maximum standard deviation. This is the maximum standard deviation in foot placement found for each approach, averaged between trials. For example, Hay’s (1988) results for elite long jumpers suggests that the variability in foot placement for the approach towards the take-off board in elite, national-class to Olympic-class long jumpers, should not exceed 25cm. Scott et al’s (1997) data supports this statement,
demonstrating variability of 58cm in novice long jumpers. As the peak standard deviation of footfall placement occurs when visual regulation emerges, the reduced variability in foot-placement of expert performers during the accelerative phase supports Tyldesley and Whiting’s (1975) conclusions, that expert performers are more capable of precisely reproducing movements.

The step prior to the target at which visual regulation emerges has also been examined within the sport of long jumping. Hay (1988) demonstrated that on average visual regulation emerges five steps prior to the target in expert performers. The running approach towards a force plate has been examined by Abendroth-Smith (1996), providing data on the emergence of visual regulation in novices. In running towards a force plate, the novice performers visually regulated the final four steps. Considerable variability exists in the step at which visual regulation emerges prior to the target for both the novice and expert performers examined, with visual regulation occurring as early as nine steps prior to the target and as late as the last step (Hay, 1988; Abendroth-Smith, 1996). One possible explanation for this variability shown in the utilisation of vision during target-directed locomotion is perhaps not only due to task experience, but also due to variations in approach speed. Although no data on target-directed locomotion exists in regards to the use of vision that directly compares walking and running, gait mode could be another factor influencing target-directed locomotion.

Gait Mode and Approach Speed

Van der Meer (1997) examined the visual guidance of walking and running towards a rod placed equal to or above the participant’s height. The participants were compelled to duck by decreasing their height by 5-10cm to accommodate the barrier
into their walking or running pattern. Van der Meer (1997) stated that gait mode as a mediating variable has been overlooked by researchers when examining target-directed locomotion but did not examine this mediating factor in her experiment. The control of locomotion towards a looming target, however, is affected by less reliable control of vertical position in space when running as opposed to walking (van der Meer, 1997). In addition, there is less control of the horizontal position in space when running, as in addition to the centre of gravity of the body falling outside of the base of support, there is no double support phase when both feet in contact with the ground. Running, therefore, consists of a series of controlled falls. It was hypothesised that approach speed, when comparing running to walking, would also affect the capacity of the observer to visually regulate step length towards a target. In walking, the time of the double support phase decreases as a function of increased approach speed (Murray, 1967). Similarly, the time of the ground contact phase, when the foot is in contact with the ground in running decreases as a function of increased approach speed (Williams, 1985). The effect of gait mode on the observer’s capacity to visually regulate locomotion towards a target was examined (Experiments 1 and 2) and, in addition, the effect of approach speed within the single gait mode of running (Experiment 3).

**Approach Distance**

A longer approach distance provides the opportunity to initiate walking or running and reach a comfortable state of locomotion and approach speed prior to responding to the looming target. The effect of a stationary target on approach velocity, therefore, decreases as a function of increasing approach distance (Bradshaw, 1997). The velocity developed from a longer approach distance, however,
must be sustained and then controlled during completion of the foot-positioning task, that is, the approach distance should not be long enough to cause fatigue and approach speed to decrease. Considerations of approach distance and velocity are applicable to real-world gait tasks in sport where the goal is to increase performance, such as in long jumping. In long jumping, the athlete attempts to develop a high velocity run to transfer the momentum from the approach into the jumping movement, in order to travel as far as possible in the horizontal direction.

The evaluation of the approach kinematics and step pattern, final foot placement with the stationary target, and approach kinematics during walking and running requires the identification of the affordances and mediating factors described, thus comprising the information that guides the action. A middle process links the information and locomotion action, the perceptual mechanisms that detect the information and action over a period of time.

**Perceptual Mechanisms for Acquiring Time-to-Contact Information in Locomotion Towards Targets**

Humans require perceptual information in order to guide them through their environment safely and effectively. When investigating how humans control their gait pattern to approach a target in their environment, exproprioceptive information regarding the position, orientation, and speed of the body relative to the environment is of primary importance. The motor program generating the coordinated pattern of locomotor movements is continually adjusted on the basis of the visual and sensory information in order to meet the demands of the terrain encountered, such as irregular surfaces and targets (Lee, 1979).
Vision can provide information about a target from a distance almost instantaneously (Patla et al., 1996). When the path and target is visible, vision alone can guide locomotion, but as in the present study, the characteristics of the end point is not always visible from the start of the approach. For example, at the beginning of an approach toward a target, characteristics such as target length may not be visible due to the visual angle of the eye with the target (Figure 2.5).

![Figure 2.5. The perception of target size from different approach distances.](image)

Visual sampling during target-directed locomotion could be influenced by the characteristics of the target such as spatial constraint (length in the anterior-posterior direction) and height. When approaching a narrow double-boundary target or a raised surface, visual regulation may increase during the approach, when compared to an approach towards a single-boundary target. Vision, however, is not limited to guiding the direction of locomotion but also plays a key role in controlling other aspects of locomotion such as speed. For example, in treadmill walking a 200ms visual sample every stride is required to prevent the drift in speed regulation that is observed in
locomotion without vision (Patla, 1996). When approach speed increases from walking to running when aiming for a target, the importance of vision was expected to increase. In experiments 1 and 2, a range of approach velocities including walking, jogging (slow running), and sprinting (fast running) was examined. Visual regulation was also examined across a range of approach velocities in running during experiment 3, to examine whether visual regulation is affected by gait mode or approach speed.

Visual input is the main function that is utilised to regulate the velocity and direction of locomotion. In addition to the regulation of self motion, as introduced earlier, visual input also enables the guidance of foot-placement in order to safely negotiate the surfaces encountered in the immediate environment. Visual input via optic flow (direct perception) is one of two theories proposed to explain the visual regulation of locomotion. An alternative explanation of the visual control of locomotion is indirect (cognitive) perception, which proposes that first-order variables such as distance, object size, and velocity can be accurately judged to obtain indirectly, time to contact information (Yilmaz & Warren, 1995). No critical test has yet been made in the literature regarding the required time to process the visual cues by either direct or indirect perception, however, it is assumed that processing time to contact information directly requires less cognitive load. The exclusive use of one model for processing time to contact information over the other is yet to be proven (Bardy & Laurent, 1991). The ecological direct perception approach was taken in the current study.

**Tau Models for Controlling Locomotion**

Visual information from the surrounding environment is utilised in the regulation of goal-directed locomotion. Optic flow is the stimulus for vision,
generated from the pattern of light at the retina of the eye as the participant moves relative to the environment. When moving, the passage of the eye through successive points of observation gives rise to the optic flow field at the eye (Gibson, 1958; Lee, 1974).

In any situation visual information can be classified into three categories; global-central visual information, global-peripheral information, and local visual information. Global-central information is generated by the motion of the participant and the resulting radial flow on the central retina. Global-central information gives the participant self-motion perception about his/her direction, distance, and speed from a target position, thus guiding the participant towards the goal. Global-peripheral information also provides self-motion perception, but is gained from target features in peripheral vision. Local visual information in the form of object motion perception (Laurent, 1991) is generated from the expansion rate of a target, and provides additional perceptual information such as the targets length to guide final foot-placement. A three-phase kinematic profile may govern the regulation of target-directed walking and running.

The kinematic profile of target-directed human gait was examined in experiments 1 and 2 to determine if there was evidence of a global visual control phase, that is, whether visual control commenced prior to the target perception threshold which identifies local visual control. Affirmation of a global visual control phase in walking and running to targets would reveal that the observer is capable of regulating step length and duration for a longer distance and time towards the position of the target when the circumstances require it. It was hypothesised that visual regulation time increases towards a narrow double-boundary target, and at higher approach speeds (Experiments 1-3). Furthermore, it was expected that visual
regulation of step length and duration would increase when approaching two targets, the take-off board and vaulting horse in gymnastics, when compared to approaching a single target, the take-off board only (Experiment 4). The perception of a difficult targeting task is gained from the optic flow specific to the affordance encountered, that is, the optic flow generated is unique to the looming surface in the immediate

(a)

![Anatomy of the eye](image)

(b)

![Optic flow diagram](image)

**Figure 2.6.** (a) Anatomy of the eye, illustrating the lens and retina (from Martini, 1998). The nodal point of the eye is through the visual axis. (b) An observer approaching a target at time $t$. The movement of the point of observation ($O$) relative to the environment generates an optic flow field in the direction of $Z$ to $0$. $P$ (Target) and $G$ (ground) denote texture elements in the environment. Light is reflected from the moving environmental texture elements passes through the nodal point of the lens of the eye, giving rise the optic texture elements $P'$ and $G'$ on the retina (from Lee, 1976).

Time-to-contact information generated from the optic flow between the retina and textured surfaces of the environment provide visual information about self-motion; specifically direction, distance, and speed from the target, as well as the necessary information to control the balance of the body during movement (Lee, 1979). In the early demonstration of optic flow, Lee (1980) examined body sway by using a floorless swinging room suspended from a high ceiling. The swinging room altered the participants' visible surroundings in order to generate optic flow fields at the eyes corresponding to forward, backward, or sideways movements of the participant.

Lee (1976) proposed a model to describe the optically perceived time-to-contact based upon Gibson's (1958) ideas of perception and action, from the optical expansion rates between an observer and an obstacle, as shown in Figure 2.6. The model represents an observer (O) at a distance (Z) from the target of size R at a particular point in time (t). The inverse rate of dilation of the visual angle (Θ) with the obstacle specifies the current distance and velocity of the observer at a given time during the approach, thus corresponding to current time-to-contact Tc with the obstacle (Bardy & Warren, 1997). The optical quantity of time-to-contact, tau (τ), is calculated as follows:

$$\tau (t) = \frac{\Theta (t)}{\Theta (t)} = \frac{Z(t)}{Z(t)} = T_c (t)$$

The detailed mathematic calculations specific to Lee's (1976) model for perceiving tau are provided in Appendix 2.
The optical variable tau specifies the time remaining before the observer will reach the target, at a given time during the walking or running approach. Tau, therefore, is an estimate of time-to-contact based upon the observer’s velocity and position at a given time. If, however, the observer either accelerates or decelerates then tau for that previous point in time will either underestimate or overestimate time-to-contact. If a narrow target influences the approach walk or run, the visual regulation of step length and duration may need to commence earlier in the approach to guide foot-placement than for a wide target. The lack of visual regulation during the gait initiation (accelerative) phase of target-directed locomotion, discussed previously in the kinematics of aiming movements, could be due to the high levels of acceleration required to initiate the walking or running action.

![Figure 2.7. Simulation of the tau (τ)/time-to-contact (T_e) relationship for constant-velocity (blue), accelerative (green) and decelerative (red) approaches (Bardy, 2001).](image)

During high levels of acceleration at the start of a walking or running approach to a target, visual regulation may not provide sufficient time-to-contact information to be utilized during this phase of the approach. This is due to the non-constant velocity of the approach towards the target, such that tau and time-to-contact are not linearly
related (Bardy, 2001) (Figure 2.7). Closer to the target, tau and time-to-contact converge reducing the timing error. Due to the convergence between tau and time-to-contact prior to the target, tau estimates from optic flow will still bring the observer to the correct temporal location (Bardy, 2001). In target-directed locomotion, it was hypothesised that visual control onset occurs when the magnitude of timing error, the difference between tau and time-to-contact, is reduced to within 10%.

Diving gannets is another example of movement timing that is subject to acceleration. Due to the airborne motion of the birds as they dive towards the water there is the action of a gravitational force. Acceleration in this case is therefore due to gravity. The magnitude of this timing error, therefore, depends on the initial height of the dive. The diving gannets streamline their body by stretching their wings back, just prior to entering the water, which enabled Lee and Reddish (1981) to examine when the gannets were visually regulating their diving approach towards the water. As tau specifies the first-order time to contact without accounting for acceleration, it overestimates the actual time before the gannet enters the water. If the gannet dives from a higher initial position then the gannet should start streamlining longer before contact. Lee & Reddish (1991) observed that the gannets were streamlining their wings at a common time-to-contact point with the water.

A limitation of Lee’s (1974) model for perceiving time-to-contact information is that the target is level with the eye, characteristic of computer simulation experimentation. Rarely in locomotion is the target at eye level; in fact, in the majority of everyday circumstances the target is at ground level. Further models for calculating tau, thus time-to-contact information, have subsequently been proposed, specifically aimed at modeling direct approaches towards a target (Lee, 1980;
Tresilian, 1991; de Rugy et al., 2000). Of specific importance to the current experiments was the tau model proposed by Tresilian (1991) (Figure 2.8).

![Figure 2.8](image)

Figure 2.8. An observer approaching a target at time t. The movement of the point of observation (O) relative to the environment generates an optic flow field in the direction of A and B to O (from Tresilian, 1991).

Tresilian (1991) addressed the perception of time to contact in the movement of animals towards surfaces in their immediate environment. When the target is below the observer's eye-level, time to contact estimates from the optic flow generated between the target surface and the observer during movement can still be judged consistent with Lee (1976). Tresilian (1991) presented two types of time to contact judgement, global tau (τ_G) and local tau (τ_L). Global tau still requires the detection of coordinates of the focus of expansion in the retinal-coordinate system; however, it utilizes the radial (locomotor line) outflow during the observer's movement. Global tau is, therefore, calculated as follows:

\[ \tau_G = \frac{Z}{\dot{Z}} \]
where \( Z \) is the distance of the observer from the target along the locomotor flow line, and \( \dot{Z} \) is the velocity of the locomotor flow line. Global tau provides time-to-contact estimates that enable the observer to monitor approach speed and initiate braking, enabling adjustments to the gait pattern to monitor the speed of the approach and to accommodate the position of the target (Bardy et al, 1992). Local tau is the reciprocal rate of dilation of the target surface image, which is consistent with the earlier tau model of Lee (1976). Local tau provides spatial and temporal information to guide final foot placement at the target. Local tau is calculated as follows:

\[
\tau_l = \frac{\Theta}{\dot{\Theta}}
\]

where \( \Theta \) is the angle of dilation of the target image surface and \( \dot{\Theta} \) is the velocity of dilation. Tresilian (1991) stated that there was no empirical data distinguishing the optical account utilising the rate of dilation of the image from the environment account, utilising distance and velocity. In the current study, Tresilian’s (1991) statement is significant as it suggests that time to contact can be estimated from the observables in the optic projection. The distance and velocity of the observer relative to a target can be observed, and the target characteristics such as height and length can also be measured. Tresilian’s (1991) account of optic flow and time to contact judgement, however, established that there were two possible levels of time to contact judgement in target-directed walking and running, global and local tau.

De Ruyt et al (2000) postulated another model for time to contact judgement, specifically for single-boundary toe targeting in treadmill walking. As opposed to utilizing the angle between two or more elements on the target surface (Lee, 1976; Tresilian, 1991), de Ruyt et al (2000) proposed the utilization of the angle between the vertical position of the eye and the eye-target direction (using one element on the single-boundary target) (Figure 2.9). Utilising the vertical position of the eye in the
model introduces the natural variability (noise) within locomotion, due to the vertical movement of the head, particularly when running. A second observation about de

![Diagram](image)

Figure 2.9. The model proposed by de Rugy et al. (2000) for calculating tau in locomotion towards a single-boundary target.

Rugy et al’s (2000) tau model was that it describes a single-boundary (single line) target and does not account for more complex surfaces such as a double-boundary target or a raised surface. De Rugy et al (2000) state that the single source of information concerning the target is predominantly sufficient in walking to a target, deriving temporal information independent of target expansion, thus utilising radial flow (global tau). Subsequent research by Warren et al (2001), however, suggests that the expansion of the target through optic flow is required to control walking (local tau). De Rugy et al (2001) have also subsequently demonstrated that time-to-contact judgements from target expansion plays a role in guiding foot placement towards a target, especially when the circumstances require it such as when constrained by a narrow target or in conflicting situations. De Rugy et al’s (2000) model for judging time to contact with a single-boundary target, therefore, presents an alternative model for global tau, but does not extend to local tau, where an observer can perceive task difficulty from the surface characteristics and guide final foot placement.
The surface characteristics that define task difficulty generally consist of the surface length in the anterior-posterior direction and the height. Humans infrequently encounter surfaces that represent constraint in the transverse (medial-lateral) plane with the exception being a wooden plank, the beam in women's gymnastics, and the tightrope in circus performance. Lee (1980) presented two theories based upon his tau model (Figure 2.6) for distance and size perception in locomotion, based upon body-scaled measurements. The first theory utilised a ground reference point and the horizontal element of the target, where the observer's height (H) represented the R-

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**Figure 2.10.** The model proposed in the current study for calculating tau in locomotion towards a target that comprises of a certain height (Y).
coordinate of the texture element on the ground. When approaching a hurdle, for example, the observer is capable of judging that the hurdle is a certain fraction of his/her own height \((Z(t)/H(t))\) where \(Z\) represents the target height and \(H\) denotes the observers height). For targets representing constraint in the anterior-posterior direction (target width), Lee (1980) suggested that the observer utilizes step length to obtain a body-scaled measurement for a targets width \((Z(t)/L)\), where \(L\) denotes the observers step length). Extending the model presented by Lee (1980), Tresilian (1991), and de Rugy et al (2000) it was, therefore, possible to develop a model for time-to-contact judgements in the target-directed locomotion examined in the current study.

The model for perceiving tau in direct walking and running approaches towards a target is shown in Figures 2.10 and 2.11. The model represents an observer approaching a target of a particular height and width at time \(t\). Time-to-contact judgements are initially optically derived from distance and velocity of the radial flow line (global \(\tau\)) and later through the inverse rate of dilation of the target image when the observer is closer to the target (local \(\tau\)). Time-to-contact judgements can also then be judged based upon the observers distance \((Z)\) from the target, and the observer’s current velocity \((\dot{Z})\), consistent with Lee’s (1974) calculations for the environmental derivation of time-to-contact. In this manner, as the target is not level with the eye, the distance from toe to target was a relative measure of eye to target distance. That is, the distance from the eye to the target, and the distance from the toe to target, are directly related and change relative to each other.

Target height (Figure 2.10) is judged based upon the observer’s height and the perception of target height from the rate of expansion of elemental points A to B, representing a body-scaled measurement. Target length (Figure 2.11) is judged based
Figure 2.11. The model proposed in the current study for calculating tau in locomotion towards a target that comprises of a certain length (X).

upon the observer’s step length, also representing a body-scaled measurement, and the distance between the boundaries of the target (defined as element points B to C), which expands as the observer moves forward. Foot length is a second method through which the observer can make a body-scaled judgement of target length
\( \frac{X(t)}{F(t)} \), where \( X \) is the target's length and \( F \) is the observer's foot length). In fact, in the final step towards the target, foot length would provide a better body-scaled judgement on the length of the target to control final foot placement.

The observer is capable of judging time-to-contact with the stationary target and body-scaled measurements of the target characteristics to regulate foot placement during a walking and running approach. Consistent with the earlier tau models (e.g. Lee, 1976), the observer's capacity to utilize the expansion rate of a target for perceptual judgements, local tau, depends on whether they are close enough to the target to perceive these characteristics.

The Target Perception Threshold and the Control of Braking to Contact a Target

The participant's capacity to utilize the optical variable local tau to estimate time-to-contact and also make judgements concerning the target's dimensions from the expansion rates of a target to guide foot placement, depends on the ability to perceive changes in angular velocity \( (\omega(t)) \) (Lee, 1976; Laurent, 1991). When angular velocity due to the expansion of the target at the retina is low, the target characteristics such as length cannot be perceived, providing no information to guide final foot placement (global tau). The perceptual threshold for perceiving angular velocity is approximately \( 12 \) deg/s (Lee, 1976), with the exact value depending on parameters such as exposure duration, the target size, luminance, and background environment (Harvey & Michon, 1974). Angular velocity for the perception of goal-directed movement is defined as:

\[
\omega(t) = \frac{\dot{w}Z}{Z(t)^2}
\]

where \( w \) is the length of the target, \( \dot{Z} \) is the approach velocity, and \( Z \) is the distance to the target at time \( t \) (Laurent, 1991).
The gradient of change in time to contact estimates during locomotion, the time derivative of tau, is a dimensionless quantity referred in the literature as tau-dot ($\dot{\tau}$). The rate of change in time-to-contact judgements (Bardy & Warren, 1997), yields information on the pattern of acceleration ($+Z$) and deceleration ($-Z$) exhibited when controlling locomotion to negotiate an obstacle. At time ($t$), tau-dot ($\dot{\tau}$) is defined as:

$$\dot{\tau} = \frac{Z_Z}{Z^2} - 1$$

where $Z$ is the distance to the target and $Z$ is the velocity at time $t$, whilst $Z$ is the acceleration of the observer between the current and previous point of observation. The mathematic calculations specific to determining the tau-dot formula from the change in tau over two points of observation is provided in Appendix 3.

To describe the control of braking collisions, researchers have studied the mean tau-dot during visual control. If deceleration ($Z$) towards a target is constant, $\dot{\tau} \geq -0.5$ specifies that the participant will stop prior to contact. When $\dot{\tau} \leq -0.5$, however, it is not possible to brake within the remaining time and distance to stop at the target. A tau-dot margin of $-0.5$ has been shown to describe the control of braking in automobiles (Trefiner, 2001). In the task of running and pushing a door (Wann et al., 1993) a mean tau-dot was found during the visual control phase of $-0.7$. Whilst the participants in that study were not required to stop at the door, a soft impact, the results cast doubt on whether the tau-dot margin of $-0.5$ describes the control of braking in all target-directed aiming movements, particularly in target-directed gait tasks. In another task from the same experiment, for example, participants ran to a picture on a wall and kissed it (Wann et al., 2000). A tau-dot of $-0.61$ described the control of braking in this task. The visual control of braking in walking and running
was, therefore, expected to be different dependent on the type of targeting task. Bardy and Warren (1991) suggested that higher tau-dot values might describe carefully controlled, gradual approaches towards a target. In the case of running to targets,

![Diagram: Information, perception and locomotion](image)

Figure 2.12. Information, perception and locomotion. The basic model in the current study for examining information-based target-directed locomotion. *In a simulated (lab-based) setting the influence of the secondary surface is verbally directed as either a hard or soft impact.
decelerations consistent with those of an automobile may not be physically possible. A tau-dot of $-0.5$, therefore, may be unlikely in human target-directed locomotion (Bardy & Warren, 1997). The tau-dot margin of $-0.5$ was examined in experiment 3 where participants were required to run towards a target and either stop (soft impact) or run-through (hard impact). It was expected that running towards a target would be governed by a tau-dot margin higher than $-0.5$.

**Summary**

The tau and tau-dot models describe the direct perception of information generated via optic flow between the eye and the target in walking and running aiming tasks. The information perceived consists of the affordances specific to the surface of the target and also mediating factors such as gender, mode of locomotion, and experience. The main focus of the current study was on the action of locomotion. The action of walking and running to a target will now be reported from a series of lab-based experiments (Experiments 1, 2, and 3), developed from the information-based perspective reviewed (Figure 2.12). The knowledge gained from the literature concerning target-directed aiming tasks and target-directed human gait, as well as the earlier experiments was then utilised to examine the real-world high-velocity task of gymnastics vaulting (Experiment 4).
Chapter 3

Effects of Approach Velocity and Foot-Target Characteristics on the Visual Regulation of Step Length
Abstract

Two questions emerge from the literature concerning the affordances and mediating variables underlying the information-based regulation of step length to a target. The first concerns the effects of approach velocity on the onset of visual control (VCO), when visual regulation of step length begins during target-directed locomotion. The second concerns the effects of different target characteristics such as the number of boundaries defining the target and height of the target on step length regulation. In two separate experiments, participants (Experiment 1&2: n=12, 6 female, 6 male) walked, jogged, or sprinted towards a target along a 10m walkway, consisting of two marker-strips with alternating black and white 0.50m markings. Each experiment consisted of three targeting tasks with the requirement to both negotiate and continue moving (run-through) through the target. Five trials were conducted for each task and approach speed, with trials block randomised between the six participants of each gender. One 50Hz video camera panned and filmed each trial from an elevated position, adjacent to the walkway. Video footage was digitized to deduce the gait characteristics. Results for the double-boundary and single-boundary targeting tasks indicate a linear relationship between approach velocity and accuracy of final foot placement (R=0.89). When foot placement was highly constrained by the target step length shortened during the entire approach. VCO was found to occur at an earlier tau-margin for lower approach velocities for both experiments, indicating that the optical variable ‘tau’ is affected by approach velocity. A three-phase kinematic profile was found for all tasks, except for the take-off board condition when sprinting. Further research is needed to determine whether this velocity affect on VCO is due to ‘whole-body’ approach velocity or whether it is a function of the differences between gait modes.
(Wrisberg & Mead, 1983). Females are conservative in spatiotemporal judgements, allowing a safety-margin for error in time to contact estimates (Schiff & Oldak, 1990). It was hypothesised, therefore, that females would place their foot further from the critical boundary defining the target, to allow a safety-margin for judgement error. When walking towards the raised surface, for example, it was expected that females would place their foot further away from the posterior edge of the surface.

A second consideration when re-assessing the contribution of earlier work on step length regulation is the possible effect of the affordances, that is, the target’s constraints on gait characteristics during the approach. Would, for example, a target that imposed less spatial constraint, or was in some way qualitatively different, such as a raised surface, also influence how individuals regulate foot position in order to successfully step on, over, or across it. Bardy and Laurent (1991) examined the approach characteristics in walking towards small and large targets, with restricted central vision. The braking distance and time-to-contact was greater when walking towards the smaller target (1.77m/1.17s) than the larger target (1.70m/1.14s). This indicates that step regulation increases when required to accommodate a target of high spatial constraint. In an experiment in which participants stepped over a target, it was shown that the target, a rod, was crossed by the heel of the lead foot at 78% of stride length independent of the obstacle’s height (Sparrow, Shinkfield, Chow and Begg, 1996). This observation suggests that step length is regulated precisely on approaching targets in order to maintain an invariant crossing position within the lead foot trajectory. Furthermore, Begg and Sparrow (2000) found that in approaching a raised surface, similar to stepping onto a roadside kerb, the position of the trail foot relative to the step edge appeared to be a critical determinant of safe clearance. Thus,
once more, step length regulation on approaching the obstacle appeared to be an important feature of successful obstacle negotiation.

Whilst there are few precedents for hypothesising the effect of target characteristics on step length regulation, Bradshaw and Sparrow (2000) revealed a linear speed/accuracy trade-off effect on approach characteristics when target length was manipulated (Bradshaw and Sparrow, 2000). In that study final stride length was found to shorten for the shorter (more spatially constrained) targets. The step characteristics of the entire approach (8 m and 12 m) were not measured in that experiment and the nature of adjustments to step length prior to the final step into the target are not known. In order to test the hypothesis that target characteristics would influence step length regulation during the approach, a variety of targeting tasks were tested as shown in Figure 3.1. It was anticipated that in both experiments

**EXPERIMENT ONE**

Double Boundary  Single Boundary-Toe  Single Boundary-Heel

**EXPERIMENT TWO**

Rod  Box  Take-Off Board

*Figure 3.1. The targeting tasks in Experiment 1 and 2.*

characteristics of the targeting tasks such as the boundaries defining the target and the foot-positioning requirement would affect the approach speed as reflected in the
kinematic profiles. In addition, it was hypothesised that the targeting task would influence step length regulation during the approach.

In the obstacle-approach literature considerable attention has been given to the question of how visual information is used to regulate step length and, in many reports, time-to-contact with the obstacle or event has been proposed to play an important role. Lee (1974), for example, proposed a model to describe the optically perceived time-to-contact from the optical expansion rates between an observer and an obstacle. The inverse rate of dilation of the visual angle (θ) with an obstacle specifies the current distance and velocity of the observer at a given time during the approach, thus corresponding to current time-to-contact \( T_c \) with the obstacle (Bardy and Warren, 1997). This optical quantity is referred to as \( \tau \) and specifies, at a given point in the approach, the time remaining before the observer will reach the obstacle. \( \tau \) is, therefore, an estimate of time-to-contact based upon the observer's velocity and position at a given time.

Further models for calculating \( \tau \) have subsequently been proposed in the literature for direct approaches towards a target (Lee, 1980; Tresilian, 1991; De Rugy et al, 2000), particularly at the global level for perceptual information such as heading, target position, and speed (global \( \tau \)). In addition to the \( \tau \) models that describe the direct perception of time to contact during constant velocity motion towards an obstacle is the observer's capacity to utilize this information from the expansion rates of a target or obstacle. The capacity to guide foot placement to negotiate the obstacle from time-to-contact information depends also on the observer's ability to perceive angular velocity \( (\omega(t)) \) (Laurent, 1991). The perceptual threshold for perceiving angular velocity is 1/12 deg/s (Lee, 1976), such that at certain distances the target may be perceived to be so small that it does not provide any
relevant information to guide the timing of the braking action (Laurent, 1991) and final foot placement. Some empirical support for local tau, perceptual judgements from the expansion rates of the object to guide final foot placement, has been provided by Laurent (1991) who investigated the changes to step length based upon time-to-contact information when approaching a target. When, in treadmill walking, his participants were provided a virtual display to simulate optic flow associated with walking faster than the treadmill velocity, step length adjustments occurred earlier in the approach towards the target, which led to an underestimation of the target position. In the foot-targeting tasks in the present experiments it was considered important to determine the effects of visual control onset (global tau) and the target’s expansion rate (local tau) on approach characteristics. In the double boundary condition in Experiment 1 (as shown in Figure 3.1), for example, it was anticipated that the increase in the perceived length as the target was approached, would influence the timing of local visual control.

The velocity at which humans either walk or run toward objects may affect the timing of global visual control onset. A tau-based interpretation of step length regulation suggests the hypothesis that with target characteristics held constant, global visual control onset is independent of approach speed and occurs at a constant value of tau.

**Experiment 1**

Experiment 1 was designed to address the information-based regulation of step length through manipulations to target type and approach speed. Specifically the changes to step length associated with the constraint imposed by a double or single boundary target was determined, and secondly, the effect of using the heel or the toe
to guide the foot to the target. Three approach speeds were also investigated, walking, jogging and sprinting, to explore the effects of ‘whole-body’ approach speed on visual regulation of step length towards the targets.

Method

Participants

Twelve volunteers, comprising of an equal number of males and females, were recruited from the undergraduate and research community at Deakin University. The participants were first screened using a medical questionnaire to ensure that they were free of musculoskeletal impairments that may have affected their gait pattern. Details concerning the participants' age and anthropometric measurements are provided in Appendix 11. The experiment was conducted according to the ethical guidelines for experimental work involving human participants laid down by the Deakin University Ethics Committee for the Department of Health and Behavioural Sciences.

Figure 3.2. The position of the panning camera and timing lights in relation to the 10m-walkway and target for Experiment 1. The strip markers, consisting of alternating black and white 0.50m intervals positioned parallel to the walkway, provided the scale reference for the analysis of the video footage, thus allowing the footfall positions and timing of the approach gait to be obtained for each trial.
Equipment and Set-Up

Figure 3.2 outlines the experimental set-up for Experiment 1. The 15m-walkway consisted of two marker strips spaced 1.22m apart, with 50cm alternating black and white intervals that provided the scale-reference for subsequent analysis of the videotape. The targets were identified with white tape 10m from the start of the approach. They comprised of a double-boundary target of equal to the width of the participant’s shoe length +3cm, and single boundary targets in which either the toe or heel of the lead foot were positioned as close as possible to the boundary, as described in Figure 3.1. Beyond the walkway was a stopping area and as a precaution, safety (crash) mats were positioned on the wall. A pair of DDH (Direct Digital Hardware) infra-red timing lights were placed at the start of the walkway and a second pair were

Figure 3.3. A typical field in the video footage of the current series of experiments, showing the order of digitisation.
Figure 3.4. The identification of visual control onset from the standard deviation of the footfall positions of five trials. The top panel shows that when locomotion is unconstrained, the standard deviation of the footfall positions continue to increase, indicating no evidence of visual control.
located adjacent to the target. One panning camera (Panasonic Super-VHS 50Hz MS4) was set-up in an elevated position, at one side of the walkway.

Design and Analysis

Video-tape footage collected from each trial was captured from either a Grundig GV 690 Super-VHS VCR or a Panasonic NV-HS800 Super-VHS VCR into computer format (*.avi file) using a Fast AV Master 2000 video capture card on a personal computer. The captured video footage was replayed, field by field, with the toe-off frame of each foot placement digitised to obtain the x,y coordinates of both the marker strip interval and the toe position (Figure 3.3). The x,y coordinate data were then inputted into an Excel program to scale the measurements and calculate the length, duration, frequency, and velocity of each step, and the standard deviation of the footfall positions. The peak standard deviation of footfall position was manually analyzed to identify the position of visual control onset and the emergence of global visual control. Visual control onset was identified as the point where the maximum standard deviation in footfall position occurs for the entire approach, provided that the standard deviations of the footfall positions then decrease in a systematic manner (Figure 3.4). Further calculations were conducted to obtain the mean of the step data for the entire approach, and the mean of the step data during visual control. The velocity and acceleration profiles for the approaches were calculated, with tau (τ=Z/\dot{Z}) and the target perception threshold calculated for the targeting tasks utilising the toe as the reference point. The target perception threshold was utilised to determine the onset of local visual control.

Accuracy of the footfall position measurements was determined in pilot work by filming cardboard “footprints” positioned on the approach strip in a way that
simulated the footfalls of normal gait. The cardboard footprint locations were measured to the nearest millimeter using a builder's steel tape. Measurements of the toe-to-board distances from the videotape analysis were found to be on average within ± 0.5cm of the measured distances. This technique is, therefore, more accurate than that previously reported in similar studies (e.g. Hay, 1988). For a more detailed account of the camera considerations, gait analysis protocol, and accuracy measures see Appendices 4 and 5.

Linear regression analyses were undertaken to determine the strength and direction of the association between approach velocity and foot-placement accuracy. Repeated measures Analysis of Variance (ANOVA) procedures were used to test the significance of difference between means for the above gait variables for each targeting task and speed condition. Entered into the initial analysis were the between-subjects factor Gender, and two within-subject factors, Task with three levels (double boundary, toe-boundary, and heel-boundary) and approach Speed (walk, jog, sprint). The data was then re-analysed with the between-subject factor Gender excluded. Condition presentation order was also included in initial analyses but in the absence of significant effects the data were re-analysed with the order factor excluded.

Results

The results are presented in three sub-sections below. The first concerns the affect of gender on the step length characteristics of the target-directed approach. The second concerns the target and speed effects on step length and frequency during the approach. The third sub-section describes the kinematic profiles of the whole-body approach as a function of both speed and target characteristics.
Gender Effects on Step Length Regulation

Equal numbers of males and females participated in experiment 1. Step length was shorter for the female participants due to the difference in the height between the participants of each gender (Table 3.1). A trend was found, indicating that step frequency was higher for the female participants. No further gender effects were found to describe the step regulation and final foot placement of the male and female participants, possibly due to an interaction between step length and frequency.

Table 3.1. The effect of gender on the gait variables during overall target-directed locomotion and during visual control onset (significant effect 0.05 level*/0.01 level**, trend 0.09 level†).

<table>
<thead>
<tr>
<th>Variable</th>
<th>F(2,11)</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>6.09†</td>
<td>1.81</td>
<td>1.69</td>
</tr>
<tr>
<td>VC Step Length (m)</td>
<td>22.39**</td>
<td>1.28</td>
<td>1.10</td>
</tr>
<tr>
<td>Step Length (m)</td>
<td>20.01**</td>
<td>1.17</td>
<td>1.03</td>
</tr>
<tr>
<td>VC Step Frequency (steps/s)</td>
<td>10.49†</td>
<td>2.66</td>
<td>2.83</td>
</tr>
<tr>
<td>Step Frequency (steps/s)</td>
<td>6.16†</td>
<td>2.69</td>
<td>2.85</td>
</tr>
</tbody>
</table>

Target Type and Speed Effects on Step Length Regulation

Summarised in Table 3.2 are the results showing the target type and approach speed effects on step characteristics during the approach. The first row of data for the target type effects indicates that target type influenced foot-positioning accuracy relative to the target boundaries. The double boundary target necessarily induced the greatest accuracy, with participants positioning their toe at an average of 1.22cm from the forward boundary. More important, however, is that for the heel of the foot was targeted significantly less accurately towards the single boundary target than the toe.
Table 3.2: The effect of the targeting task and whole-body approach speed on the gait characteristics during the approach, at visual control onset (VCO) and during visual control (VC) in Experiment 1. Significant main effects starred (**0.01/*0.05). Pairwise significant effects numbered where different to 0.05 level (*double/toe/heel and ^walk/jog/sprint).

<table>
<thead>
<tr>
<th>Gait Characteristic</th>
<th>Target Type</th>
<th>F(2,11)</th>
<th>Double</th>
<th>Toe</th>
<th>Heel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy (m)</td>
<td></td>
<td>108.74**</td>
<td>0.01**</td>
<td>0.07**</td>
<td>0.19**</td>
</tr>
<tr>
<td>SD_{Max}</td>
<td>ns</td>
<td>0.31</td>
<td>0.25</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Step Length (m)</td>
<td></td>
<td>37.65**</td>
<td>1.07**</td>
<td>1.10**</td>
<td>1.14**</td>
</tr>
<tr>
<td>Step Frequency (steps/s)</td>
<td></td>
<td>6.73*</td>
<td>2.75**</td>
<td>2.79**</td>
<td>2.78**</td>
</tr>
<tr>
<td>VC Steps (n)</td>
<td></td>
<td>6.20*</td>
<td>4.92</td>
<td>4.08**</td>
<td>5.36**</td>
</tr>
<tr>
<td>VC Duration (s)</td>
<td></td>
<td>9.38**</td>
<td>2.45</td>
<td>2.01**</td>
<td>2.67**</td>
</tr>
<tr>
<td>VCO Distance (m)</td>
<td>ns</td>
<td>5.07</td>
<td>4.59</td>
<td>5.24</td>
<td></td>
</tr>
<tr>
<td>Tau</td>
<td>ns</td>
<td>2.00</td>
<td>1.82</td>
<td>2.10</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gait Characteristic</th>
<th>Approach Speed</th>
<th>F(2,11)</th>
<th>Walk</th>
<th>Jog</th>
<th>Sprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy (m)</td>
<td></td>
<td>7.91**</td>
<td>0.07**</td>
<td>0.09**</td>
<td>0.12**</td>
</tr>
<tr>
<td>SD_{Max}</td>
<td>ns</td>
<td>0.28</td>
<td>0.32</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td></td>
<td>215.74**</td>
<td>1.62**</td>
<td>3.12**</td>
<td>4.92**</td>
</tr>
<tr>
<td>Step Length (m)</td>
<td></td>
<td>250.71**</td>
<td>0.82**</td>
<td>1.13**</td>
<td>1.35**</td>
</tr>
<tr>
<td>Step Frequency (steps/s)</td>
<td></td>
<td>228.76**</td>
<td>1.98**</td>
<td>2.74**</td>
<td>3.60**</td>
</tr>
<tr>
<td>VC Steps (n)</td>
<td></td>
<td>42.20**</td>
<td>7.03**</td>
<td>4.28**</td>
<td>3.06**</td>
</tr>
<tr>
<td>VC Duration (s)</td>
<td></td>
<td>77.06**</td>
<td>3.99**</td>
<td>2.00**</td>
<td>1.14**</td>
</tr>
<tr>
<td>VCO Distance (m)</td>
<td>ns</td>
<td>5.54</td>
<td>4.82</td>
<td>4.54</td>
<td></td>
</tr>
<tr>
<td>Tau</td>
<td></td>
<td>77.06**</td>
<td>3.46**</td>
<td>1.56**</td>
<td>0.89**</td>
</tr>
</tbody>
</table>
As anticipated, step length was also affected by the target constraints with the double boundary target associated with shorter steps. The data in Table 3.2 also reveal that the requirement to target the single boundary with the heel significantly influenced the number of steps visually regulated during the approach. Whilst more steps were visually regulated when guiding the heel, this adaptation did not result in more accurate foot positioning. Step length, frequency, and velocity were not different between the single boundary targets. In summary, the greater the constraint of the target due to more than one boundary, the shorter the steps during the approach, resulting in a higher step frequency and an associated decrease in approach velocity.

Characteristic of increasing approach speed, summarised in Table 3.2, it can be seen that the steps increase in frequency and lengthen during the approach. Aside from these inherent characteristics of gait linked to increasing approach speed was the accuracy of final foot placement with an increase in approach speed. As can be seen in the first row of data for the approach speed effects, foot-positioning accuracy decreases with an increase in approach speed. The foot was positioned, when averaged across the three target manipulations, 7cm from the boundary when walking, increasing to 9cm when jogging, and 12cm when sprinting. Evidence of a speed/accuracy trade-off was found ($F(2,11) = 108.742$, $p < 0.01$, $y = 93.015x - 290.28$, $r = 0.89$), possibly due to the shortening of the steps to position the foot accurately within the constraint of the targeting task, resulting in a loss of velocity.

Of considerable interest was the point of visual control onset in the approach towards the targets, specifically, the effect of approach velocity on this variable. The point of visual control onset was influenced by approach velocity as shown in Table 3.2. and Figure 3.5. Visual control onset occurred 3.99s prior to the target when walking, considerably longer than the onset of visual regulation at 2.00s and 1.14s
prior to the target when jogging and sprinting respectively. Approach velocity, however, had no effect on the distance prior to the target at which visual control onset emerged. Visual control onset began on average 4.97 m from the target. In regards to the time-to-contact estimate, tau, it was found that visual control onset emerged earlier when walking (τ=3.46), then when jogging (τ=1.56) and sprinting (τ=0.89).

![Visual Control Onset](image)

**Figure 3.5.** The time-to-contact estimate, as defined by tau, at which visual regulation emerged.

**Whole-Body Approach Kinematics**

The kinematic profile provides further insight into the step regulation required to negotiate a target at the three approach speeds. The velocity/time profile in Figure 4.3 shows that there is an initial rapid step to accelerate the body from rest, followed by a decrease in velocity until the participant reaches a comfortable state of locomotion and heading or direction of travel towards the target. It is at this point that visual control onset occurs. As the target characteristics such as width cannot be perceived at this point in the approach (Table 3.3), it indicates that some other form of visual regulation is occurring.
Figure 3.6. The average velocity, acceleration, and tau/time profiles for target-directed walking, jogging, and sprinting.
A clear profile for these tasks can also be seen when looking at the time-to-contact estimate \( \tau \) (Figure 3.6). The initial fluctuations in velocity causes an increase in the time-to-contact estimate based on the optical variable \( \tau \) beyond the initial prediction seen in the first step, thus increasing the prediction of time-to-contact from the optic array. Once \( \tau \) has reached a level that is below the initial prediction of time-to-contact at the initial step, i.e. time-to-contact based on the optical variable \( \tau \) is decreasing in a systematic manner and the magnitude of timing error is reduced, visual control onset occurs.

**Table 3.3.** Time remaining to the target when visual control onset (VCO) occurs and the target perception threshold (TPT) is reached in Experiment 1, with the percentage of visual control after the target perception threshold has been reached, thus, the local visual control phase.

<table>
<thead>
<tr>
<th></th>
<th>Double</th>
<th>Toe</th>
<th>Heel</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VCO</td>
<td>VCO</td>
<td>VCO</td>
<td>VCO</td>
</tr>
<tr>
<td>Walk (s)</td>
<td>3.91</td>
<td>3.29</td>
<td>4.78</td>
<td>3.99</td>
</tr>
<tr>
<td>(%)</td>
<td>19.2</td>
<td>15.8</td>
<td>18.4</td>
<td>18.1</td>
</tr>
<tr>
<td>Jog (s)</td>
<td>2.22</td>
<td>1.72</td>
<td>2.06</td>
<td>2.00</td>
</tr>
<tr>
<td>(%)</td>
<td>19.4</td>
<td>29.7</td>
<td>28.2</td>
<td>25.5</td>
</tr>
<tr>
<td>Sprint (s)</td>
<td>1.21</td>
<td>1.03</td>
<td>1.19</td>
<td>1.14</td>
</tr>
<tr>
<td>(%)</td>
<td>24.8</td>
<td>29.1</td>
<td>24.4</td>
<td>26.3</td>
</tr>
<tr>
<td>Mean (s)</td>
<td>2.45</td>
<td>2.01</td>
<td>2.68</td>
<td>2.38</td>
</tr>
<tr>
<td>(%)</td>
<td>20.0</td>
<td>21.9</td>
<td>21.6</td>
<td>21.4</td>
</tr>
</tbody>
</table>

When the period of visual control is analysed in finer detail, the period that the participant can perceive the target characteristics such as target length can be determined. As can be seen in Table 3.3, time-to-contact information can be gained
from the optic array induced by the expansion of the obstacle for only a portion of the period of the approach, approximately 21%, which is visually controlled. This suggests that another method of visual control is being utilised during the initial phase of visual control in target-directed locomotion, such as a global method of visual control where the participant controls their footfalls in the direction of the target in a time-based or distance-based manner.

**Final Step Regulation**

An in-depth analysis of the final step into the target yields information on how the target is negotiated and the constraint on foot-placement. As can be seen in Figure 3.7, the type of target being negotiated affects the placement of the foot prior to the

![Figure 3.7: Foot placement when negotiating the target for the three targeting tasks.](image)

target. When placing the heel with a single boundary target, the foot is placed closer to the target, 0.74m, where as when placing the toe with a single boundary target the foot is placed further away from the target, 1.37m. In the double-boundary targeting
task where the participant was constrained to a foot-placement accuracy of only 3cm, the final step into the target shortened to a length of 1.04 m. Approach speed also had an effect on the final step. The final step was shorter in length when walking, 0.65 m, than when jogging, 1.00 m, and sprinting, 1.56 m (F(2,11)=189.24, p<0.00).

Discussion

The affordances and mediating variables affecting the visual control of goal-directed locomotion was investigated in the current experiment utilising three targeting tasks and three approach speeds. At the same time, the kinematic profile of goal-directed locomotion was also studied.

The characteristics of the target such as the number of boundaries and foot-positioning requirement were shown to affect the footfall pattern for the whole approach. Specifically, step length shortened for the target-type of greater difficulty, reducing approach velocity. The target characteristics, therefore, has a direct influence on visual control onset, such that people adjust their gait to accommodate a target in a manner that suits the circumstances of the situation.

Approach ‘whole-body’ speed was shown to also affect the onset of visual control. Visual control onset occurs earlier in lower approach speeds. The pattern for the affects of speed on visual control onset could be due to the fact that people are less experienced at approaching targets at higher speeds, as people spend the greater majority of their lives walking rather than jogging or sprinting.

The kinematic profile for target-directed locomotion exhibited a three-phase pattern based upon the identification of visual control onset and the target perception threshold. As target characteristics such as length or the number of boundaries could not be perceived visually at the beginning of visual control during the approach, it
suggests that there are two types of visual control consistent with Tresilian (1991). There are two hypotheses for this visual regulation based on the results, either the participant can perceive their time-to-contact based on the direct perception of their position and current velocity consistent with de Rugy et al’s (2000) model, or that they can perceive their time-to-contact from the radial flow in the optic array generated from the position of the object.

In summary, the kinematic profile of target-directed locomotion exhibits a three-phase pattern. An accelerative phase where the participant commences their approach towards a target and reaches the necessary speed of the locomotor task, a global visual control phase, where the participant controls their footfalls towards the position of the target, and a local visual control phase, where the participant regulates their footfalls to negotiate the target.

**Experiment 2**

Experiment 2 was designed in conjunction with Experiment 1. Experiment 1 examined the effects of target characteristics and approach speed on the visual regulation of step length. Experiment 2 differed to Experiment 1 in that it addressed the same variables in relation to different types of real-world targets. Specifically, a raised surface, a raised rod, and a take-off board were utilised to explore the effects of these obstacles on step length regulation. The three ‘whole-body’ approach speeds, walking, jogging, and sprinting, were again utilised to examine the effect of approach velocity on visual regulation of step length.
Method

Participants

Twelve volunteers from the undergraduate and research community at Deakin University were utilised in Experiment 2, comprising of equal numbers of male and female participants. They were first screened using a medical questionnaire to ensure that they did not have musculoskeletal impairments that may affect their gait whilst walking, jogging, or sprinting. Details concerning the participants’ weight and anthropometric data are provided in Appendix 12. Experiment 2 was conducted according to the ethical guidelines for experimental work involving human participants laid down by the Deakin University Ethics Committee for the Department of Health and Behavioural Sciences.

Equipment and Set-Up

The experimental set-up for Experiment 2 was consistent with the set-up of Experiment 1, except for the targets utilised. The targets at the end of the walkway consisted of a raised 45cm platform (60cm wide), which the participants stepped onto, an easily displaced metal rod positioned above the ground at 50% of trochanterion (leg) length, which the participants stepped or hurdled over, and a 1.20m gymnastics take-off board, which the participants landed onto with two feet and then jumped off.

Procedure

At the beginning of the testing session the participants had their height, weight, and trochanterion length measured. Participants were instructed to step over the rod and to step onto the raised surface (box). For the take-off board, participants were instructed to place their foot prior to the board in a position that would allow
them to then land onto the take-off board with two feet. Participants were advised as
to where the optimum take-off position was on the board. Participants were further
instructed to continue moving after negotiating the obstacle. For example, in the rod
task participants were instructed to continue moving after clearing the rod. For the
take-off board participants were instructed to jump and land onto the landing mat. The
procedure for the remainder of the testing session was consistent with the procedure
outlined in Experiment 1.

Design and Analysis

The design and analysis procedure employed in Experiment 1 was again
utilised in Experiment 2.

Statistical analysis was conducted using linear regressions and repeated
measures Analysis of Variance (ANOVA) using SPSS for Windows to test for linear
relationships and to determine to significance of difference between tasks and
conditions. For each experiment, three within-subject factors (raised surface, rod,
board) were entered into the analysis. Each within-subject factor had three levels of
velocity of particular order. Order and gender effects were also tested.

Results

Gender Effects on Step Length Regulation

Equal numbers of males and females participated in Experiment 2. The steps
of the female participants were shorter, possibly due to their shorter stature when
compared to the male participants (Table 3.4). Step frequency was higher for the
female participants, which explains why no further gender effects were found in
relation to the other gait variables. A gender effect was found for the average foot-
position at which each target was negotiated with the females, for example, clearing the rod and landing closer (male 1.04m, female 0.97m). The final foot position from the forward boundary for the 45cm high and 60cm wide box was 0.05m for the males and 0.03m for the females. The final position of the feet on the 1.20m take-off board was 0.30m from the forward boundary for the males and 0.25m for the females.

Table 3.4. The effect of gender on the gait variables during overall target-directed locomotion and during visual control (VC) (significant effect 0.05 level*/0.01 level**).

<table>
<thead>
<tr>
<th>Variable</th>
<th>F (2,11)</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td></td>
<td>1.82</td>
<td>1.63</td>
</tr>
<tr>
<td>VC Step Length (m)</td>
<td>7.61*</td>
<td>1.29</td>
<td>1.18</td>
</tr>
<tr>
<td>Step Length (m)</td>
<td>9.21**</td>
<td>1.15</td>
<td>1.08</td>
</tr>
<tr>
<td>VC Step Frequency (steps/s)</td>
<td>5.80*</td>
<td>2.73</td>
<td>2.74</td>
</tr>
<tr>
<td>Step Frequency (steps/s)</td>
<td>11.14**</td>
<td>2.77</td>
<td>2.74</td>
</tr>
<tr>
<td>Position (m)</td>
<td>147.84**</td>
<td>0.46</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Target and Speed Effects on Step Length Regulation

The results showing the target type and approach speed effects are summarized in Table 3.5. The type of target being negotiated was shown to affect a number of gait variables, the first of these being the effect of each target on the approach step pattern. When negotiating the rod set at a height of 50% of leg length, the participants landed at an average distance of 1.01m from the rod. The raised surface (box) induced the greatest task constraint with a width of 0.60m in combination with a height of 45cm. Participants negotiated the raised surface placing
Table 3.5. The effect of the target task and whole-body approach speed on the gait characteristics during the approach, at visual control onset (VCO), and during visual control (VC) in Experiment 2. Significant main effects starred (**p<0.01/*p<0.05). Pairwise significant effects numbered where different to 0.05 level (¹board/²box/³rod and ⁴walk/⁵jog/⁶sprint).

<table>
<thead>
<tr>
<th>Gait Characteristic</th>
<th>Target Type</th>
<th>F(2,11)</th>
<th>Board</th>
<th>Box</th>
<th>Rod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position (m)</td>
<td></td>
<td>149.91**</td>
<td>0.27²,³</td>
<td>0.04¹,³</td>
<td>1.01¹,²</td>
</tr>
<tr>
<td>SDₘₐₓ (m)</td>
<td>ns</td>
<td>0.37</td>
<td>0.37</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>Step Length (m)</td>
<td></td>
<td>10.00**</td>
<td>1.12³</td>
<td>1.09³</td>
<td>1.14¹,²</td>
</tr>
<tr>
<td>Step Frequency (steps/s)</td>
<td></td>
<td>11.08**</td>
<td>2.76</td>
<td>2.78³</td>
<td>2.71²</td>
</tr>
<tr>
<td>VC Steps (n)</td>
<td>ns</td>
<td>5.14</td>
<td>5.00</td>
<td>5.56</td>
<td></td>
</tr>
<tr>
<td>VC Duration (s)</td>
<td>ns</td>
<td>2.50</td>
<td>2.48</td>
<td>2.93</td>
<td></td>
</tr>
<tr>
<td>VCO Distance (m)</td>
<td>ns</td>
<td>4.91</td>
<td>5.25</td>
<td>5.47</td>
<td></td>
</tr>
<tr>
<td>Tau</td>
<td>ns</td>
<td>2.00</td>
<td>1.97</td>
<td>2.31</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gait Characteristic</th>
<th>Approach Speed</th>
<th>F(2,11)</th>
<th>Walk</th>
<th>Jog</th>
<th>Sprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position (m)</td>
<td></td>
<td>20.87**</td>
<td>0.34⁵,⁶</td>
<td>0.42⁴,⁶</td>
<td>0.57⁴,⁵</td>
</tr>
<tr>
<td>SDₘₐₓ</td>
<td>ns</td>
<td>0.33</td>
<td>0.39</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td></td>
<td>253.52**</td>
<td>1.62⁵,⁶</td>
<td>3.10⁴,⁶</td>
<td>4.79⁴,⁵</td>
</tr>
<tr>
<td>Step Length (m)</td>
<td></td>
<td>363.43**</td>
<td>0.83⁵,⁶</td>
<td>1.16⁴,⁶</td>
<td>1.36⁴,⁵</td>
</tr>
<tr>
<td>Step Frequency (steps/s)</td>
<td></td>
<td>123.44**</td>
<td>1.94⁵,⁶</td>
<td>2.71⁴,⁶</td>
<td>3.60⁴,⁵</td>
</tr>
<tr>
<td>VC Steps (n)</td>
<td>5.26*</td>
<td>6.86⁵,⁶</td>
<td>4.75⁴</td>
<td>4.08⁴</td>
<td></td>
</tr>
<tr>
<td>VC Duration (s)</td>
<td>18.70**</td>
<td>4.17⁵,⁶</td>
<td>2.21⁴,⁶</td>
<td>1.54⁴,⁵</td>
<td></td>
</tr>
<tr>
<td>VCO Distance (m)</td>
<td>ns</td>
<td>5.08</td>
<td>5.03</td>
<td>5.52</td>
<td></td>
</tr>
<tr>
<td>Tau</td>
<td>12.78**</td>
<td>3.36⁵,⁶</td>
<td>1.66⁴</td>
<td>1.27⁴</td>
<td></td>
</tr>
</tbody>
</table>
their toe 0.04m from the edge anterior to the foot. The gymnastic take-off board had a width of 1.20m. Participants placed both toes 0.27m from the front boundary.

The data in Table 3.5 revealed the effect of the obstacles on step frequency and length during the approach. The higher the constraint of the obstacle task the shorter the steps were during the approach (Table 3.5), resulting in a higher step frequency. The raised platform had an average step length of 1.09m and a step frequency of 2.78 steps/s during the approach. Where as, the rod, had an average step length of 1.14m and a step frequency of 2.71 steps/s.

The effect of approach speed is also summarised in Table 3.5. As in Experiment 1, the changes to the gait characteristics associated with an increase in approach speed were again shown clearly in the results. The length and frequency of the steps increased, resulting in an increase in approach velocity. Of greater interest is the affect of approach speed on foot positioning. Foot positioning when averaged across the three obstacles, increased in distance from the key boundary of the obstacle, when approach speed increased. The pattern concerning the influence of approach velocity on visual control onset indicated a significant effect on the timing of visual regulation. Visual control onset occurred earlier when walking ($\tau=3.36$), then when jogging ($\tau=1.66$), or sprinting ($\tau=1.27$).

**Whole-Body Approach Kinematics**

The kinematic profile characteristic of approaches towards targets was consistent with the findings of experiment 1 in respect to the velocity/time, acceleration/time, and tau/time profiles.
Table 3.6. Time remaining to the target when visual control onset (VCO) occurs and the target perception threshold (TPT) is reached in Experiment 2, with the percentage of visual control after the target perception threshold has been reached, thus, the local visual control phase.

<table>
<thead>
<tr>
<th></th>
<th>Board VCO</th>
<th>Board TPT</th>
<th>Box VCO</th>
<th>Box TPT</th>
<th>Rod VCO</th>
<th>Rod TPT</th>
<th>Mean VCO</th>
<th>Mean TPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walk</td>
<td>3.82</td>
<td>2.78</td>
<td>3.82</td>
<td>1.59</td>
<td>4.86</td>
<td>1.26</td>
<td>4.17</td>
<td>1.88</td>
</tr>
<tr>
<td>(%)</td>
<td>72.8</td>
<td>41.6</td>
<td></td>
<td></td>
<td>25.9</td>
<td></td>
<td>45.1</td>
<td></td>
</tr>
<tr>
<td>Jog</td>
<td>2.25</td>
<td>2.02</td>
<td>1.38</td>
<td>2.32</td>
<td>0.79</td>
<td>2.21</td>
<td>1.40</td>
<td></td>
</tr>
<tr>
<td>(%)</td>
<td>89.8</td>
<td>67.0</td>
<td></td>
<td></td>
<td>34.1</td>
<td></td>
<td>63.4</td>
<td></td>
</tr>
<tr>
<td>Sprint</td>
<td>1.44</td>
<td>1.52</td>
<td>1.57</td>
<td>0.71</td>
<td>1.60</td>
<td>0.50</td>
<td>1.54</td>
<td>0.91</td>
</tr>
<tr>
<td>(%)</td>
<td>105.6</td>
<td>45.2</td>
<td></td>
<td></td>
<td>31.3</td>
<td></td>
<td>59.0</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>2.50</td>
<td>2.11</td>
<td>2.48</td>
<td>1.23</td>
<td>2.93</td>
<td>0.85</td>
<td>2.64</td>
<td>1.40</td>
</tr>
<tr>
<td>(%)</td>
<td>84.4</td>
<td>49.6</td>
<td></td>
<td></td>
<td>29.0</td>
<td></td>
<td>53.0</td>
<td></td>
</tr>
</tbody>
</table>

When analysing the results in finer detail a three-phase pattern was found for all of the obstacles, as shown in Table 3.6, with the exception being the take-off board where a two-phase pattern emerged when sprinting. In target-directed locomotion explored in experiment 1, a three-phase pattern of motor control was found for the targeting tasks. In experiment 2 it was found that visual control onset occurs after the perception threshold for the take-off board when sprinting (Figure 3.8) providing evidence of a two-phase pattern, an accelerative phase and a local visual control phase. Due to this difference found for the take-off board and its applications to the real-world task of gymnastics vaulting, it was decided to analyse this obstacle in finer detail.
Figure 3.8: The kinematic profile for the take-off board and raised platform tasks.
Take-Off Board

In approaches towards a gymnastic take-off board there was no evidence found of a speed/accuracy trade-off with respect to the placement of the feet on the take-off board. Novice participants placed their feet, on average, 27cm from the front anterior edge of the board across the different approach speeds. A linear relationship

![Graph showing the relationship between velocity and last footfall position.]

\[ y = 0.2289x - 0.2141 \]

\[ R^2 = 0.9741 \]

![Bar chart showing sprint, jog, and walk categories with their respective step lengths and proportions.]

**Figure 3.9.** The position of the last footfall prior to the take-off board in relation to approach velocity, and final step length, plus the proportion of final step length which is prior to the edge of the take-off board.
was found between the position of the last footfall prior to the take-off board and approach velocity ($F(2,11)=17.043, \ p<0.01, \ y=0.2289x-0.2141, \ r=0.99$). The distance from the closest edge of the board and the last footfall increases with an increase in velocity (Figure 3.9), suggesting that there is an interaction between the last footfall and the placement of the feet on the board. The interaction between the last two foot positions allows the participant to land onto the board with minimum loss in velocity and also optimum posture for take-off. As a result of the interaction between the final footfall position and the position of the feet on the board, final step length increases with an increase in velocity from 1.14m when walking, 1.37m when jogging, to 1.83 when sprinting ($F(2,11)=24.329, \ p<0.01$). Due to this increase in step length, the percentage of step length at which the closest edge of the board is crossed, increases, from 19.06% for walking through to 47.55% when sprinting ($F(2,11)=29.217, \ p<0.01$), related directly to the placement of the final footfall (Figure 3.9). To counterbalance this increase in final step length at higher velocities, the step prior to this shortens in sprinting, to maintain velocity, balance, and also to land with optimum take-off posture (Figure 3.10).

![Graph](image_url)

**Figure 3.10.** The step length profile for the sprinting approach towards the take-off board.
The distance from the take-off board at which visual control onset occurs for novices in experiment 2 is unaffected by approach velocity. Visual control onset occurs on average 4.91m from the take-off board (Figure 3.11). Visual control time, however, was affected by approach velocity for the take-off board. Visual control time was shorter when sprinting, 1.43s, then when jogging, 2.25s, and walking, 3.83s.

Figure 3.11. The distance and time at which visual regulation emerged when approaching the take-off board.
(F(2,11)=8.068, p≤0.01). Visual control onset occurs on average for a set percentage of 58-60% of approach time prior to the obstacle. When analysing visual control onset in relation to the optical variable ‘tau’ it can be seen that there is an effect by approach velocity (F(2,11)=8.080, p≤0.01). Visual control onset occurs earlier in approaches towards the take-off board when walking (τ=3.33), then when jogging (τ=1.74), and sprinting (τ=0.94).

**Rod and Raised Platform**

The results of the analysis of the take-off board provided interesting results for this real-world task in gymnastic activities. Like the take-off board, it was decided to analyse the other obstacle conditions in finer detail, but only for the final stride. The results for the final stride to negotiate the rod indicates a velocity effect

![Diagram of Rod and Raised Platform](image)

**Figure 3.12.** Mean final stride length and the proportion of this, which is prior to the edge of the obstacle for the rod and raised platform (box).
(F(1,11)=7.718, p<0.01) for the percentage of step length at which the rod was crossed, increasing from 28.59% when walking, to 36.13% when jogging, and 41.41% when sprinting (Figure 3.12). A significant velocity effect was not found, however, for the percentage of stride length at which the rod was crossed, occurring on average 63.65% of stride length. This indicated that the final step length increased with an increase in approach velocity, with the step prior to this decreasing, so that the rod was cleared at a common percentage of the overall stride.

The pattern that emerged for the final stride for the raised platform indicates a velocity effect for the percentage at which the edge of the raised platform was cleared during the final stride. The percentage at which the edge of the raised platform was cleared was lower when walking, 68.90%, than for jogging, 76.86%, and sprinting, 81.01% (F(2,11)=26.10, p<0.01) (Figure 5.6). A similar velocity effect was found for the final step (F(2,11)=31.179, p<0.01), which indicates that both of the final steps in the approach towards the raised platform increases in length with an increase in velocity.

Discussion

In the experiment 2 the affordances and mediating variables affecting visual control during target-directed locomotion was investigated utilising three types of real-world targets, a rod, a raised platform, and a take-off board. Three approach speeds were tested, walking, jogging, and sprinting. The kinematic profile was studied for the target-directed locomotion and in finer detail for each condition to determine whether the approach exhibited a two-phase or three-phase pattern of motor control.

The targeting task affected step regulation for the whole approach. Specifically, step length shortened for the more constraining raised platform (box) and
the take-off board, resulting in an increased step frequency, indicating that the
obstacle task does have a direct influence on visual control onset. Furthermore, it
indicates that people adjust their gait to accommodate an obstacle in a manner that
suits the circumstances of the situation.

‘Whole-body’ approach speed was shown to affect the onset of visual control.
Visual control onset occurred at an earlier tau-margin for lower approach speeds
possibly again due to the practice effect suggested in experiment 1, as people spend
the greater majority of their lives walking, rather than jogging or sprinting.

With the exception of the take-off board when sprinting, the target-directed
locomotion exhibited a three-phase pattern based on the identification of visual
control onset and the target perception threshold. The approach to the target consists
of an initial accelerative phase, a global visual control phase, and a local visual
control phase. The take-off board task when sprinting exhibited a two-phase pattern as
visual control onset occurred after the target perception threshold was already
reached. This suggests that in the novice participants utilised, that visual control
could occur earlier. The consistency in final foot placement found for the take-off
board, exhibiting no speed/accuracy trade-off characteristics could be due to two
possible reasons. The first of these is that the target length for the take-off board of
1.20m is above the cut-off point for constraint by a target, suggested as 0.57m by
Bradshaw and Sparrow (2000). Secondly, this could be due to the interaction found
with the placement of the last footfall before the board. The interaction found between
the last footfall and the placement of the feet on the board, allows the participant to
land onto the board with minimum loss in velocity and optimum posture for take-off.
If the position of the last footfall is not optimum then the placement of the feet onto
the take-off board will be inaccurate e.g. landing onto the back of the board. This
problem, commonly seen in elite level gymnastics, could be due to a speed/accuracy effect found only within the different sprinting speeds, such as that found by Bradshaw and Sparrow (2000). Thus, showing no evidence across approach speeds or at the lower approach velocities, or could be caused by the constraint of the second obstacle, the vaulting horse.

The percentage of final stride length at which the rod was cleared was found to be independent of velocity, occurring at 63.65%. This is considerably lower than the 78% crossing of the rod in the final stride found by Sparrow et al (1996). However, in the study by Sparrow et al (1996) the heel was used as the reference marker, whereas in the current experiments the toe was used as the reference marker. When the data for the rod in the present experiment is re-calculated using the average foot length of the participants, the average crossing of the rod during the final stride increases to 73.48%. This is more consistent with the findings of Sparrow et al (1996), which found that crossing of the rod occurred at 81% of final stride length for males and 75% for females.

**General Discussion**

Experiments 1 and 2 addressed the information-based regulation of target-directed locomotion. The effect of affordances, that is, the characteristics of a target was examined, as well as two mediating variables, approach velocity and gender.

The action of target-directed walking and running exhibits a specific kinematic pattern. The velocity/time profile shows that there is an initial rapid step to accelerate the body from rest, followed by a period of adjustment where the velocity briefly decreases until the participant reaches a comfortable state of locomotion and heading or direction of travel. Visual control onset, that is when the participant adjusts his/her
steps to negotiate the target or obstacle, emerges once the participant has reached a comfortable state of locomotion and heading. Furthermore, consistent with Lee and Reddish’s (1991) study of plummeting gannets and Bardy (2001), the tau/time profile indicated that during gait initiation, a period of high acceleration, the magnitude of timing error was high. The timing error during this accelerative phase in locomotion towards a target, increased at higher approach velocities such as when sprinting.

In optimum circumstances the action of walking, jogging or sprinting towards a target, is governed by a three-phase pattern of motor control, an accelerative phase, a global visual control phase, and a local visual control phase. A two-phase pattern, an accelerative phase and a local visual control phase, however, was found for the take-off board task when sprinting. The pattern of motor control for the take-off board may not be ideal, with results indicating that visual control onset could occur earlier as visual control emerges after the target perception threshold has been reached, that is, the participant can perceive obstacle characteristics such as width but does not use this information until later in the approach. As suggested earlier, this could be due to the larger target length of this obstacle, which is above the cut-off for constraint due to target width of 0.57cm suggested by Bradshaw and Sparrow (2000).

The targets examined constrained step length regulation for the whole approach, with the number of defining boundaries and other qualitative differences being the main circumstances (affordances) underlying this. Visual control onset is affected by approach velocity, with visual control onset occurring systematically earlier at lower approach velocities. It is not known whether this pattern found in both experiments is an effect of whole-body velocity or if it is an effect due to the differences in the gait modes for walking, jogging, and sprinting. The magnitude of timing error during the accelerative phase could explain the delayed regulation of step
length at higher approach velocities. The effect of approach velocity on visual control onset could also be due to practice as walking is a part of everyday life, where as jogging and sprinting are less practiced in everyday life, usually limited to recreational and sporting pursuits. The pattern concerning the magnitude of timing errors and the emergence of visual regulation for walking, jogging, and sprinting indicates that approach velocity is a mediating factor in target-directed locomotion. Underlying this outcome for approach velocity, however, was the possible effect of gait mode.

Schiff and Oldak (1991) stated that in time to arrival judgements of pedestrians and automobiles that females allowed a safety margin for error in time to contact judgements, possibly due to a behavioural tendency towards conservatism when compared to males. When a targeting task contained a height component, such as the raised surface, the females placed their foot close to the forward edge of the platform, leaving a large safety margin in regards to the rear boundary. Similarly, when crossing the rod the females landed closer to the rod, suggesting that if the toe-trajectory was examined during clearance, that the females left a large safety margin for foot clearance. The take-off board presented a different scenario as the females placed their feet closer to the forward boundary of the board. Placement of the feet closer to the critical boundary in this example, however, would be advantageous as that section of the board yields a greater return of potential energy. Due to increased stature, the male participants in both experiments had a longer step length. Gender had no effect on overall step velocity as a trade-off existed where the longer step length of the male participants was associated with reduced step frequency. Thus, inconsistent with Wrisberg and Mead’s (1983) suggestions, there was no evidence of a gender effect due to the larger muscular action of the male participants.
In summary, affordances such as height of a surface encountered in targeting tasks and mediating variables of approach velocity and gender, effects step regulation for the entire approach in target-directed locomotion. Furthermore, there is evidence that humans are more highly skilled at negotiating obstacles at lower approach velocities due to a lower magnitude of timing error. Further research is needed to distinguish whether the effect of approach velocity in target-directed locomotion was due to the differences in the gait modes or whether it is a general phenomenon associated with ‘whole-body’ approach velocity.
Chapter 4

The Effects of Target Length on the Visual Control of Step Length

for Hard and Soft Impacts
Abstract

Adjustments to gait were examined when positioning the foot within a narrow target at the end of an approach for two impact conditions, hard and soft. Participants (n=12, 6 female, 6 male) ran towards a target of three different widths along a 10m walkway, consisting of two marker-strips with alternating black and white 0.50m markings. Five trials were conducted for each target width and impact task, with trials block randomised between the six participants of each gender. One 50Hz digital video camera panned and filmed each trial from an elevated position, adjacent to the walkway. Video footage was digitised to deduce the gait characteristics. A linear speed-accuracy trade-off between target length and approach time was found for both impact tasks (R=0.99, p<0.01; R=0.96, p<0.05). For the hard impact task, visual control time increased linearly (R=1.00, p<0.05) when whole-body approach velocity decreased. Visual control time was unaffected by whole-body approach velocity in the soft impact task. A constant tau-margin of 1.08 describes the onset of visual control when approaching a target whilst running, with the control of braking during visual control described by a tau-dot of −0.54. Future research is needed to examine the control of braking in different targeting tasks.
Introduction

Three distinct phases govern the control of locomotion towards a target, based upon the initiation of the walking or running strides and the optic flow generated between the eye of the observer and the affordances encountered. A parallel can be drawn between optic flow field and fluid flow (Kim, Turvey, & Carello, 1993). In fluid flow, such as the movement of air on an aircraft's wing, the Reynolds number divides smooth laminar flow from turbulent flow. In fluid flow, therefore, there are two different modes that a fluids energy is distributed, smooth or turbulent. The optic flow field could be illustrated, in a similar manner to the energy states in fluid flow, as containing distinct informational states.

During gait initiation and acceleration of the observer, the magnitude of timing error from the optic flow field is large, due to the high levels of acceleration. Thus, the accelerative phase of walking or running to a target, comprises a low informational state in regards to the optic flow field. Visual regulation of step length and duration emerges after the observer has reached a comfortable state of locomotion and heading, yielding two informational levels, a global state and a local state. Global visual regulation comprises temporal and spatial information regarding the position of the target and the speed of the approach. Local visual regulation comprises temporal and spatial information regarding the position of the target and its characteristics, such as length or height.

The timing of the informational states is governed by the affordances encountered, such as the number of explicit boundaries, the spatial constraint, or height. Furthermore, in the earlier experiments it was demonstrated that information states are possibly mediated by the observers approach speed, gait mode, or both. It was established that global visual regulation emerges earlier when traversing at lower
approach velocities, such as when walking, resulting in accurate final foot placement with the affordances encountered. In the current experiment the effect of target length on the visual control of running was examined to determine whether information states are affected by approach speed and/or gait mode. It was expected that gait mode would be a mediating factor affecting visual regulation not approach velocity. Thus, a common tau margin was hypothesised to describe target-directed running.

The type of impact associated with the action of walking or running to a target can be classified into two categories. A hard impact, such as in long jumping where the participant continues to move after the target contact, and a soft impact, where the participant stops within the target zone, such as when stopping at the kerb prior to crossing the road (Kim et al, 1993). It was expected that visual control onset would occur earlier for soft impacts due to the requirement to contact the target with zero final velocity. In a soft impact task the observer must decelerate to finish at the target with zero final velocity. In a hard impact task the observer must decelerate at the level required to safely negotiate the target. Laurent, Tornadre, and Bovet (1987) demonstrated that in a soft impact task, temporal proximity is the relevant dimension for the initiation of braking. In Laurent, Tornadre, and Bovet’s (1987) study, participants ran towards a plastic hurdle utilising a range of running velocities (3.36m/s to 9.24m/s), stopping just prior to contact. Braking to stop at the hurdle occurred at a common tau margin of 1.03s, however, the time and distance from the hurdle which braking commenced increased at higher approach speeds.

Laurent (1991) stated that the earlier emergence of braking at higher approach velocities depended on the observer’s braking ability, establishing that a relationship must exist between optic flow and the kinetic properties of braking. In the earlier experiments, however, it was revealed that across a variety of hard impact gait tasks,
visual regulation emerged earlier at lower approach velocities. Furthermore, it was revealed that the greater visual regulation when walking enabled earlier adjustments to the timing and length of each step. The earlier modifications to the step pattern resulted in greater accuracy of final foot placement with the target, suggesting a possible explanation for the speed/accuracy trade-off observed in target-directed gait tasks (Bradshaw & Sparrow, 2000). Whilst this still suggests a link between the optic flow and the control of gait, the patterns of deceleration warrant further attention.

Yilmaz and Warren (1995) explored the patterns of deceleration during the visual control of automobile braking in closed-loop displays of approaches to a road-sign, generated on a computer with a spring-loaded mouse used as a brake. In this soft impact task, a tau-dot (τ) strategy of −0.5 governed the control of deceleration towards the road-sign, based upon the change in the time-to-contact (τ) estimate from the optic flow generated as the road-sign increased in size when the observer approached it. When tau-dot was below −0.5, deceleration was too low, and when tau-dot was above −0.5, deceleration was too high, whereas when running and pushing a door (Wann et al., 1993) a mean tau-dot of −0.7 describes the homing-in phase. It is possible, therefore, that the control of braking in targeting tasks is a function of both task constraints and braking capacity.

The braking capacity of the system, whether biological or mechanical (e.g. an automobile), depends on the maximum braking force that can be developed by the observer. The evolution of walking and running capability might have been tightly constrained by the requirement of sensitivity to tau-dot (Kim, Turvey & Carello, 1993). Kim, Turvey and Carello (1993) stated that tau-dot is the possible provision for a lawful optical basis for determining the adequacy of forces for an intended contact. Highly mobile biological systems greater than 0.001kg in weight must keep their
momentum exchanges with targets within certain limits to avoid injury. Kornhauser (1964) asserted that harm would occur to a biological system, whatever species or body size, if the velocities before and after contact differ by 7.62m/s. As illustrated by Wann (1993) the control of braking in human gait may not be governed by a tau-dot of -0.5. In the present experiment it was hypothesised that a tau-dot of -0.6 would describe running towards a target, with a tau-dot greater than -0.6 describing braking to stop at the target, a soft impact, and a tau-dot less than -0.6 describing a hard impact with the target.

The purpose of the current experiment, therefore, was to examine the visual control of braking in running towards targets of different lengths, to determine the effect of hard and soft impacts, as well as affordances such as target length and gait mode.

Method

Participants

Twelve young healthy volunteers, comprising equal numbers of male and female participants, were recruited from the undergraduate and research community of Deakin University. They were screened using a medical questionnaire to ensure that they were currently engaged in at least two sessions of physical activity a week and were free of musculoskeletal impairments, such as knee or ankle injuries, that may have affected their gait. Participants with a history of training in sporting skills such as long jumping and gymnastics vaulting were specifically excluded from the study. Details concerning the participants' age and anthropometric measurements are provided in Appendix 13. The experiment was conducted according to the ethical guidelines for experimental work involving human participants laid down by the
Deakin University Ethics Committee for the Department of Health and Behavioural Sciences.

![Diagram](image)

**Figure 4.1.** Experimental set-up.

**Equipment and Set-Up**

Figure 4.1 outlines the experimental set-up for experiment 3, which was consistent with the set-up of experiment 1 and 2, except for the targets utilised. The targets at the end of the walkway consisted of two brightly coloured balsa wood strips, spaced at a width of the participants shoe length + 5/10/15cm.

**Procedure**

At the beginning of the testing session participants had their height, weight, and shoe length measured and reflective markers were attached to the ankle, toe and heel to ensure maximum visibility for later videotape analysis. Participants were instructed to run as fast as possible from the start of the walkway and place their foot within the target area at the end. For the soft impact task they were asked to stop with their foot within the target and in the hard task to continue running or "run-through"
following contact within the target area. It was strongly emphasized that they would be asked to repeat the trial if they contacted one of the target strips, and that if more than one error was committed by contacting the target strips, then they would repeat that entire block of five trials\(^1\). They then completed one practice trial followed by five experimental trials at each target length (shoe length + 5cm, 10cm, or 15cm in length) for each impact task, a total of 30 trials. Presentation order for each of three target-widths was completely counterbalanced within each task type with one male and one female participant assigned to each of the six presentation orders. Half of the participants undertook the hard contact task first followed by the soft task with the order reversed for the others.

![Diagram of footfall](image)

**Figure 4.2.** The components of the step; step length (SL) and time (ST), braking time (BT), thrust time (TT), ground contact time (GCT), and flight time (FT).

\(^1\) The average error rate was 11.39%, which equated to 0.57 errors out of 5 trials. The highest error rate recorded was for the +5cm target length with 0.94 errors out of the 5 trials.
Design and Analysis

Video-tape footage collected from each error-free trial was captured from a Sony DVCam DSR-20P VCR using a Fast AV Master 2000 video capture card on a personal computer. The captured video footage was replayed field by field with the toe-off frame of each step digitised to obtain x,y coordinates of both the marker strip interval and the toe position. Time of initial ground contact, mid-support, and toe-off was also recorded. The x,y coordinate data for toe at toe-off were then inputted into an Excel program to calculate step length. From these time and position data the duration, frequency, and velocity of each step were calculated. Ground contact, braking, thrust, and flight times were also calculated, as shown in Figure 4.2. The peak standard deviation of footfall position was obtained and taken as representing visual control onset. Further calculations were conducted, consistent with the procedures for experiments 1 and 2, to obtain the mean of the step data, the mean of the step data during visual control onset, and the velocity, acceleration, tau, and tau-dot profiles for the running approaches. Tau-dot (τ) was calculated as follows:

\[ \tau = \frac{\ddot{Z}}{Z^2} - 1 \]

The effect of impact type and target length on the dependent measures was determined using a two-way repeated measures Analysis of Variance (ANOVA). Two within-subject factors (Impact task 1&2) were entered into the analysis, with three levels of target length (Target length 1,2&3). The between-subject effects of order and gender were initially included in the analysis. In the absence of any order effects and having noted any gender effects, these factors were removed from the analysis and the data re-analysed. Post-hoc analysis included one-way repeated measures analysis of
variance (ANOVA) to examine each within-subject factor separately (Impact task 1&2) with the three levels of target length. Linear regression analysis was also performed to test the relationship between target length and movement time, approach velocity and visual control time, and approach velocity and tau.

**Results**

Significant main effects for impact type and target length described the approach kinematics and a variety of the gait parameters, however, results of the two-way ANOVA failed to show any significant impact type by target length interactions. Firstly, the effect of gender on the gait parameters will be presented.

*Table 4.1.* The effect of gender on the gait variables during target-directed locomotion and during visual (VC) (significant effect 0.05*/0.01**, trend 0.09*).

<table>
<thead>
<tr>
<th>Variable</th>
<th>F(2,11)</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>13.19*</td>
<td>1.79</td>
<td>1.69</td>
</tr>
<tr>
<td>VC Step Length (m)</td>
<td>4.56†</td>
<td>1.48</td>
<td>1.33</td>
</tr>
<tr>
<td>Step Length (m)</td>
<td>10.30*</td>
<td>1.38</td>
<td>1.24</td>
</tr>
<tr>
<td>VC Step Frequency (steps/s)</td>
<td>ns</td>
<td>3.13</td>
<td>3.11</td>
</tr>
<tr>
<td>Step Frequency (steps/s)</td>
<td>ns</td>
<td>3.13</td>
<td>3.13</td>
</tr>
</tbody>
</table>

**Gender Effects on Step Length Regulation**

Equal number of males and females participated in Experiment 3. The average step length of the male participants was 1.38m in comparison to 1.24m for the female
participants (p=0.042) (Table 4.1). The steps of the male participants were longer possibly due to their higher stature. No further gender effects were found to describe the gait variables such as step frequency or step velocity.

**Target Length and Impact Task Effects on Approach Kinematics**

When spatially constrained by a target, gait parameters and resulting ‘whole-body’ velocity are adjusted to accommodate the targeting requirements of the task. It can be seen from Figure 4.3 that for both hard and soft impact tasks (p=0.002, p=0.044) approach time increased for the narrower targets. Subsequent pair-wise comparisons of the target length means for the hard and soft impact tasks indicated that the movement times for the narrowest target (SL+5cm) was significantly longer than for the SL+10cm target (hard p=0.044, soft p=0.045) and the SL+15cm target (hard p=0.014, soft p=0.010). In the hard impact task, movement time for the SL+10cm target was also significantly longer than the SL+15cm target (hard p=0.001). Furthermore, results of the regression analysis revealed a linear function for the hard and soft impact tasks (r=0.99, r=0.96). The slope for the linear function was consistent between impact tasks (hard: y=-0.0271, soft: y=-0.0238), with a y-intercept of 2.527 for the hard impact task and a y-intercept of 2.648 for the soft impact task. This result demonstrates that movement time increased in the soft impact task, when compared to the hard impact task (p=0.003) by a systematic margin.
Within each impact task, the spatial constraint of the target had different effects on approach velocity, as shown in Table 4.2. Table 4.2 shows that approach velocity was significantly lower for the soft impact task both at the onset of visual control (soft p=0.007) and during the visual control phase (soft p=0.000). Target length had no effect during the accelerative phase of the soft impact task, indicating an initial ballistic phase, whereas a shorter target caused a decrease in approach velocity at visual control onset and during visual control. For the soft impact task, velocity increased until the onset of visual control, subsequently decreasing to allow the foot to be positioned within the target with zero final velocity.
Table 4.2. Approach velocity in the accelerative phase (Acc), at visual control onset (VCO), and the visual control phase (VC) for three target lengths (shoe length +5/10/15cm) under the hard and soft impact tasks.

<table>
<thead>
<tr>
<th>Impact Task</th>
<th>Hard</th>
<th>Soft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>Target Length (cm)</td>
<td>Target Length (cm)</td>
</tr>
<tr>
<td>(m/s)</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Acc</td>
<td>4.008</td>
<td>4.274</td>
</tr>
<tr>
<td>VCO</td>
<td>4.296</td>
<td>4.564</td>
</tr>
<tr>
<td>VC</td>
<td>4.338</td>
<td>4.712</td>
</tr>
</tbody>
</table>

Figure 4.4. The three phases for the approach for a hard and soft impact with the target.

An examination of the kinematic profile of the approach provides insight into the regulation of velocity to negotiate targets under the two impact conditions. As shown in Figure 4.4, when expressed as a percentage of approach time, the accelerative phase was similar for the two impact tasks. With respect to the visual
control phase, however, a greater proportion of time in the soft impact task was controlled locally (p=0.002), that is, closer to the target when target characteristics can be perceived and step length adjusted accordingly. It was, therefore, during the visual control phase that impact task affected the approach kinematics.

Target Length and Impact Task Effects on Step Length Regulation

Visual control onset was not influenced spatially by either target length or impact task, occurring on average 4.68m from the target for the 10m approaches. A significant ANOVA main effect indicated that the time of visual control onset was dependent on target length (p=0.035). Specifically, for the hard impact task as target length reduced visual control onset time increased (p=0.046) with visual control onset at 1.68s, 1.42s, and 1.21s from the target for the three target lengths respectively (SL+5/10/15cm). When constrained to stopping within the target there was no effect of target length on visual control time, with visual control onset at 1.68s, 1.36s, and 1.61s from the target for the three targets of increasing length (SL+5/10/15cm). When visual control time was examined in relation to the ‘whole-body’ approach velocity for the hard impact task, a linear relationship ($y = -0.9569x+5.5123, r=1.00$) described an increase in visual control time at lower approach velocities.

Prior to examining the control of braking in the two target-directed gait tasks, the onset of visual control in relation to the optical variable tau was examined. Contrary to the hypothesis that visual control onset would occur earlier for shorter targets and for a soft impact, there were neither target length nor impact affects on visual control onset, with a constant tau-margin of 1.08 (SD 0.23) found. In contrast, a trend was found for target length in the hard impact task (hard p=0.052), with visual
control onset at tau-margins of 1.28, 1.06, and 0.97, for the short to long target lengths respectively.

![Graphs showing Hard Impact and Soft Impact](image_url)

**Figure 4.5.** The tau-dot/time profile for the three targets of increasing spatial constraint. The top panel shows the pattern found for the hard impact task, whilst the lower panel shows the pattern for the soft impact task.

When tau-dot, the rate of change of the optical variable tau, was examined during the visual control phase, it can be seen that visual control onset emerged just prior to the initiation of braking. As shown in Figure 4.5, an average tau-dot of -0.45
Table 4.3. Step characteristics in the accelerative phase (Acc) and the visual control phase (VC) of the target approaches, for the three target lengths (shoe length +5/10/15cm), in the hard and soft impact tasks.

<table>
<thead>
<tr>
<th>Gait Variable</th>
<th>Hard Impact</th>
<th>Soft Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Target Length</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>$SD_{Max}$ (m)</td>
<td>0.120</td>
<td>0.191</td>
</tr>
<tr>
<td>Step Length (m)</td>
<td>1.259</td>
<td>1.370</td>
</tr>
<tr>
<td>VC</td>
<td>1.383</td>
<td>1.469</td>
</tr>
<tr>
<td>Step Time (s)</td>
<td>0.326</td>
<td>0.318</td>
</tr>
<tr>
<td>Acc</td>
<td>0.327</td>
<td>0.317</td>
</tr>
<tr>
<td>VC</td>
<td>0.114</td>
<td>0.117</td>
</tr>
<tr>
<td>Flight Time (s)</td>
<td>0.128</td>
<td>0.129</td>
</tr>
<tr>
<td>Acc</td>
<td>0.080</td>
<td>0.073</td>
</tr>
<tr>
<td>VC</td>
<td>0.078</td>
<td>0.071</td>
</tr>
<tr>
<td>Braking Time (s)</td>
<td>0.127</td>
<td>0.123</td>
</tr>
<tr>
<td>Acc</td>
<td>0.122</td>
<td>0.117</td>
</tr>
<tr>
<td>VC</td>
<td>0.248</td>
<td>0.260</td>
</tr>
<tr>
<td>Step Length (m)</td>
<td>1.272</td>
<td>1.291</td>
</tr>
<tr>
<td>Acc</td>
<td>1.351</td>
<td>1.369</td>
</tr>
<tr>
<td>VC</td>
<td>0.343</td>
<td>0.327</td>
</tr>
<tr>
<td>Step Time (s)</td>
<td>0.355</td>
<td>0.336</td>
</tr>
<tr>
<td>Acc</td>
<td>0.110</td>
<td>0.112</td>
</tr>
<tr>
<td>VC</td>
<td>0.116</td>
<td>0.118</td>
</tr>
<tr>
<td>Flight Time (s)</td>
<td>0.093</td>
<td>0.086</td>
</tr>
<tr>
<td>Acc</td>
<td>0.100</td>
<td>0.095</td>
</tr>
<tr>
<td>VC</td>
<td>0.138</td>
<td>0.127</td>
</tr>
<tr>
<td>Thrust Time (s)</td>
<td>0.140</td>
<td>0.124</td>
</tr>
</tbody>
</table>
was found for the hard impact task, indicating significantly less braking than observed in the soft impact task with a tau-dot of -0.55 (p=0.04). A significant main target length effect was evident for the impact tasks (p=0.023). An average tau-dot of -0.48, -0.45, and -0.43 described the approach towards the targets of increasing length in the hard impact task. In the soft impact task, an average tau-dot of -0.57, -0.55, and -0.54 characterized the approach towards targets of increasing length. Thus, a tau-dot of -0.54 describes the control of braking in the approach tasks investigated.

The control of approach velocity to negotiate the target required adjustments to the step mechanics, which have been summarised in Table 4.3. The first observation is that a common feature of the step characteristics of the approach was that there was no influence of target length or impact task on flight time. The two impact tasks were, however, distinguished by differences in braking time between the accelerative (p=0.000) and visual control phases (p=0.000). For the hard impact task, braking time decreased from 0.073s to 0.071s of each foot-strike between the accelerative and visual control phases. Braking time increased between the accelerative and visual control phases from 0.088s to 0.094s in the soft impact task due to the requirement to control the approach to stop within the target.

**Final Step Length Regulation**

The final foot position prior to the target is critical to optimal foot placement within the target area. The final footfall distance prior to the target for the hard impact task, as shown in Figure 4.6, increased from 0.88m (SD 0.38m) to 0.99m (SD 0.33m) and 1.06m (SD 0.33m) for targets of increasing length, consistent with the increase in approach velocity. For the soft impact task, however, the final footfall placement prior to the target was unaffected by target length, with a mean distance of 0.54m (SD
0.23m) from the target. Foot placement prior to the target was, therefore, closer for the soft impact task than for the hard impact task that occurred on average 0.98m from the target (p=0.000). For all target lengths and impact tasks there were no significant differences in placement of the toe within the target area. The toe was placed consistently 1.89cm (SD 0.66cm) from the anterior boundary of the target.

Figure 4.6: Final foot position prior to the target for the hard impact targeting task.

Discussion

The control of braking is operated within the limits of a body’s tolerance for foot-ground reaction forces. Mechanical systems such as automobiles are designed to brake at a rate that maximises adaptability to hazards on the road but also to maintain a safe level of changing force for the occupants. The control of braking in automobiles has been described by a tau-dot of −0.5 (Lee, 1976). Biological systems similarly operate within their physical limits. When running to targets, the control of braking is described by a tau-dot of −0.54. This finding suggests that human runners possess a similar braking capacity to that of automobiles.
The control of braking observed in target-directed running and the changes in velocity further illustrates the human body's threshold for force tolerance. When constrained to stopping at the target, the running approach velocity during the accelerative phase was slower and the amount of braking during visual control increased, described by an average tau-dot of -0.55. Conversely when there was no requirement to stop at the target, running approach velocity during the accelerative phase increased, and the amount of braking during visual control decreased, described by a tau-dot below -0.54. Wann et al.'s (1983) study of running and pushing a door demonstrated when braking is constrained by an "implicit" target. The participants needed to brake early to enable stable foot-position relative to the doorway for the door to be pushed open. Braking in their task would, therefore, have occurred earlier and at a faster rate than for the explicitly bounded foot-targeting tasks in the present experiment, thus being described by a tau-dot of -0.7. As has been illustrated, the affordances encountered such as the target characteristics and the requirement to stop affect the control of braking.

Further analysis of the data from the experiments reported in Chapter 3 on hard impact foot-targeting when walking, jogging, and sprinting describes the effect of gait mode on the control of braking. A mean tau-dot of -0.41 illustrated the light braking adjustments required to complete the hard impact tasks. A significant main effect did not differentiate the braking observed in the hard impact tasks when walking, jogging, and sprinting. Greater braking was, however, evident in the sprinting tasks (mean tau-dot of -0.34) when compared to jogging (mean tau-dot of -0.41) and sprinting (mean tau-dot of -0.47). It appears, therefore, that braking decreases slightly at higher approach speeds in hard impact gait tasks; further reduced by the fact that braking occurs later and for a shorter duration. An examination of the
temporal and spatial characteristics of visual control onset in target-directed locomotion further identifies how the body is controlled to both adapt to the immediate surroundings and also remain below the threshold for breakdown.

![Graph](image)

**Figure 4.7.** The effect of approach velocity on visual regulation in hard impact target-directed locomotion of novice performers.

The emergence of visual regulation and braking in running to stop at a target was described by a tau-margin of 1.08, which was consistent with the onset of braking in Laurent, Tornadre, and Bovet's (1987) study of running and stopping at a hurdle.
When comparing the results to the earlier experiments it was revealed that gait mode, not approach velocity, affects visual regulation in target-directed locomotion when constrained to stopping at the target. When not constrained to stopping at the target (hard impact), however, a trend could be seen for the relationship between approach velocity and visual regulation. As can be seen in Figure 4.7, when examining target-directed running for the hard impact task across experiments 1, 2, and 3, a curvilinear effect of approach velocity on visual regulation time and tau is observed. Visual regulation in target-directed running decreases at higher approach velocities. Visual regulation in target-directed running, such as long jumping and gymnastic vaulting would, therefore, be expected to begin at a tau-margin of at least 1.08, increasing slightly with lower approach velocities. Visual regulation in tasks such as long jumping and gymnastics vaulting allows precise step length regulation during the approach to ensure optimum foot placement at the target.

Foot position within the target was found to be highly consistent, approximately 1.89cm from the anterior boundary of the target, suggesting that the forward boundary was utilized to guide foot positioning. Footfall position prior to the target appears to be the key to successful foot placement within the target. When required to stop within the target, the final foot position prior to the target was consistently 0.54m from the target, in order to allow the participant to place their foot within the target with zero final velocity, independent of spatial constraint. When zero final velocity was not required, however, the final footfall position prior to the target increased in distance, occurring on average 0.98m from the target, increasing for targets of greater length, due to the higher approach velocity and, thus, longer average step length. Thus, as suggested by Begg and Sparrow (2000), step length regulation during the approach is critical for accurate final foot placement relative to the target.
Consistent with earlier work (Bradshaw & Sparrow, 2000), a speed/accuracy trade-off was found for the two impact tasks, demonstrating that when locomotion was constrained by the requirement to contact a narrow target, approach time increased. The decrease in approach velocity induced by the spatial constraint of a target indicates that people adjust their gait to accommodate a target in a manner adapted to the affordances encountered. When negotiating a cluttered environment, the speed/accuracy trade-off phenomenon may be critical to understanding how humans safely negotiate a target in gait tasks. In a highly constrained situation people shorten their steps and slow down to safely negotiate a target. However, in the sporting domain, where the highest level of performance is aspired and harm is minimised through the use of impact absorbing and softened surfaces, this everyday speed/accuracy trade-off mechanism that may protect people from harm could actually be hampering performance.

The findings of the current experiment also confirmed that in target-directed locomotion, the approach comprises of three phases, an accelerative phase, a global visual control phase, and a local visual control phase. Spatial constraint of the target influenced velocity for the entire approach in the hard impact task. In the soft impact task, however, there was an initial ballistic phase where target length had no effect on approach velocity. Thus, the spatial constraint of the target had no effect on movement velocity during the accelerative phase of the approach when the movement requirement was to stop within the target. A further characteristic of the soft impact task was that a greater proportion of the approach was visually controlled locally when the participant could perceive target characteristics such as length. The requirement to stop within the target was therefore characterised by movement time increasing closer to the target.
In summary, the type of impact with the target affected step regulation for the approach to targets when running. Spatial constraint of the target also affected step regulation in the hard impact task. A speed/accuracy trade-off was found to describe the relationship between approach movement velocity and target constraint. The onset of visual regulation emerged at a constant tau-margin of 1.08, with a tau-dot of -0.54 describing the visual control of braking. Further research is needed to examine the braking capacity of different biological and mechanical systems, such as the control of locomotion in children, or the control of aircraft braking on a landing strip. The effect of experience in the information-based regulation of target-directed locomotion also warrants further attention. Specifically, it is suggested that the approach step length and duration characteristics of expert performers should be examined in a real-world high-velocity foot-targeting task and, in addition, the effects of the approach on performance.
Chapter 5

The Approach Towards the Take-Off Board and the Horse in

Women's Gymnastic Vaulting
Abstract

The approach step, hurdle, and round-off length characteristics of women’s vaulting were examined in relation to the effect of the vaulting horse constraint, post-flight performance and judge’s score. Five female gymnasts aged 13-15 years completed five trials for each of the two experimental tasks. In the first task the gymnasts performed round-off entry vaults. In the second task the gymnasts utilized the same vaulting approach distance, completing a round-off entry onto the take-off board followed by a backward stretched salto onto 1.25m high landing mats. Two reference strips with 50cm black and white intervals were placed on each side of the approach area. One 50Hz-panning camera filmed the approach, with two stationary 250Hz cameras filming the post-flight vaulting performance. Two qualified judges viewed each vaulting trial and provided a performance score. The panning video footage was digitized to deduce the toe-to-board distance of each footfall and the timing of each step. The high-speed video footage was analyzed three-dimensionally to obtain the performance measures such as post-flight height. In the non-vaulting task, visual regulation decreased when approach velocity increased, consistent with the regulation of step length in novice performers. In the vaulting task, however, visual regulation increased when approach velocity increased, indicating that the aptitude of expert performers is partly due to their ability to visually regulate for a greater time and distance during the approach. A significant correlation was found between velocity during visual control of the approach, post-flight time (p≤0.01) and judge’s score (p≤0.01). Specifically, increased approach velocity leads to increased round-off velocity (p≤0.01), resulting in a short high velocity take-off from the board (p≤0.01).
Introduction

Considerable research has focused upon the kinematic characteristics of gymnastic vaults (e.g. Takei et al, 2000). One shortcoming of the extant literature is that the key kinetic input for vaulting, the running approach, has received very little attention. A precise and consistent high-velocity approach in gymnastics vaulting leading to optimum foot-placement on the board has been suggested to be critical for successful performance. Bruggemann and Nissen (1981), for example, demonstrated that a higher approach velocity was associated with a higher score from qualified judges. The association between approach velocity and performance was due to a high correlation between approach velocity and post-flight height ($r=0.78$) and distance ($r=0.83$). More recently Krug, Knoll, and Zocher (1998) demonstrated that vaults of greater difficulty required a higher level of running speed during the approach. It would appear, therefore, that gymnasts should be trained to run faster during the approach to increase vaulting difficulty and, thus, improve performance.

Whilst research to date has shown the importance of approach velocity on gymnastic vaulting performance, the control of the approach run has not been adequately investigated to ascertain the important aspects of the approach and how accurate final foot position on the take-off board can be accomplished. In gymnastics vaulting and other sporting activities requiring fast approaches towards a target, such as long jumping, the athlete must not only approach at high speed but also negotiate one or more obstacles before executing the required movement when in flight. The aim of the experiment reported here was twofold. The first aim was to determine the influence of the targets (affordances) formed by the take-off board and vaulting horse on the characteristics of the approach, in particular approach speed. The second aim
was to investigate the effect of the approach on performance in gymnastics vaulting, as measured by judge’s scores.

![Diagram](image)

**Figure 5.1.** The targets and obstacles in gymnastics for forward entry (handspring and tsukahara entry) vaults (a). For round-off (yurchenko) entry vaults there are three implicit targets; the position of the foot during the hurdle phase, the position of the foot during the step into the round-off, and the position of the hands during the round-off. The gymnast lands onto the board in a backward entry (facing away) from the vaulting horse (b).

In gymnastics vaulting there is generally two targets and one obstacle, as shown in Figure 5.1. The first target is the position of the foot during the hurdle prior to the board, where the gymnast takes off from one foot in a hop-like action to land onto the board with two feet. The second target is the foot-position on the (1.20m long) take-off board, and finally, the obstacle to be negotiated is the vaulting horse (1.25m high for women, 1.35m high for men). The exception to this type of approach is when the gymnast executes a “yurchenko” round-off entry vault, which involves
four targets and one obstacle. The two extra targets in yurchenko vaulting is the placement of the step into the round-off and the placement of the hands during the round-off. The round-off occurs directly after the hurdle, allowing the gymnast to contact the board backwards. The hurdle to the board movement is described as the transition section of the approach, where the momentum gained from the run-up is transferred to the take-off. In the current experiment the approach step, hurdle and round-off phases was examined in relation to an approach towards the take-off board with and without the additional constraint of the vaulting horse. The influence of the vaulting horse on approach velocity was specifically targeted as it was expected that approach velocity would decrease when additionally constrained by the vaulting horse.

As already indicated, there are two requirements of a successful run-up in gymnastics vault, they are high approach speed and accuracy of foot placement on the take-off board (Hay, 1993). A speed/accuracy trade-off describes target-directed running (Bradshaw & Sparrow, 2000), however, the length of the gymnastics take-off board is above the spatial constraint required to induce a speed/accuracy trade-off. Unlike long jumping and pole-vaulting that have approaches in the range of 40-60m, gymnastics vaulting requires an approach distance of only 15-25m from the vaulting horse. Hay (1993) suggested that due to the shorter approach it is possible for gymnasts to develop a stereotyped step pattern that is more consistent in approach speed and positioning of the feet in the hurdle and on the take-off board, than for long jumping. In addition Hay (1993) argued that the gymnasts approach in vaulting would be expected to be more consistent due to the greater number of repetitions during training. Standardizing the approach in gymnastics vaulting is, however, not a
standard training practice. With respect to coaching practice, approach characteristics of vaulting deserves further investigation.

![Diagram](image)

**Figure 5.2.** The length of each step in the approach when running unconstrained and when approaching a gymnastics take-off board and vaulting horse (adapted from Meeuwsen and Magill, 1987).

A study by Meeuswen and Magill (1987) is the only previous work examining the visual regulation of step parameters during the approach phase in gymnastics vault. In their study six female gymnasts were filmed performing three handspring vault approaches and two unconstrained sprints. The vaulting approach sprints differed from the unconstrained sprints because there was evidence of spatial and temporal adjustments to the steps, particularly in the last two steps and the hurdle. The point at which visual regulation of step length and duration emerged during the approach was not examined. As can be seen from the Meeuswen and Magill (1987) data presented in Figure 5.2, a direct comparison between the step length pattern when unconstrained and constrained demonstrates the effect of the targets on step length regulation. The steps when running unconstrained were longer when compared to
target-constrained running as early as the sixth step from the start, lengthening further
during the approach. The exception was the last step when vaulting, which lengthened
during the execution of the hurdle step. The similarity between the two tasks in step
length during the first five steps suggests a common initial accelerative phase that
may not rely on visual control, consistent with the target-directed gait tasks examined
in the earlier experiments. The regulation of the hurdle step demonstrates how the
final steps of the approach are adjusted to accommodate the target in gymnastics
vault.

The current experiment was designed to examine the step, hurdle, and round-
off length characteristics of the approach towards the take-off board and the vaulting
horse in elite women’s gymnastics. In addition, it was of interest to demonstrate how
the approach affects vaulting performance as reflected in the judge’s score. The
gymnasts were asked to complete two tasks. The first was a yurchenko entry vault
with a start value greater than 8.9. The second task was a running approach towards a
take-off board with the vaulting horse removed and completing a round-off onto the
board with a backward stretched salto onto a landing mat. It was expected that when
the vaulting horse was removed that visual regulation time would decrease and
approach velocity would be greater for the approach run due to the lower constraint of
the task when constrained by only one obstacle, the take-off board. When constrained
by both the take-off board and vaulting horse it was expected that the capacity to
visually regulate the approach longer would be associated with a faster approach and a
higher performance score.
Method

Participants

Five elite female gymnasts were utilized in this experiment. The gymnasts ranged in age from 13-15 years and had a range of competitive experience, from Junior Nationals through to Junior International Competitions. Details concerning the participants' age and anthropometric characteristics are provided in Appendix 14. The experiment was conducted according to the ethical guidelines for experimental work involving human participants laid down by the Deakin University Ethics Committee for the Department of Health and Behavioural Sciences.

Equipment and Set-Up

Figure 5.3 outlines the experimental set-up. The vaulting podium consisted of an approach strip, take-off board (American Athletic Incorporated), a vaulting horse (Acromat), and a landing mat. The take-off board was marked with white 0.45m wide tape 0.60m on either side from the rear boundary. Two marker strips were placed on either side of the approach strip, with alternating 50cm black and white intervals that provided the scale reference for the subsequent analysis of the videotape. One panning camera (Sony Digital Camcorder DSR-200AP 50Hz) was set up on an elevated platform to one side of the approach strip. Two stationary cameras (Redlake MotionScope PCI 500S) were set-up, oblique left-front and oblique right-back, at the side of the vaulting area, with an angle between the optical axes of the cameras of approximately 80°. The high-speed cameras were operated at a frequency of 250Hz and a shutter speed of 1/500s. A 4.0m high calibration rod (2.5 x 2.5 x 2.5 cm) marked with 0.5m intervals was filmed in six positions to provide a three-dimensional scale-reference for the stationary cameras.
Figure 5.3. The experimental set-up, which consists of an approach strip, take-off board, vaulting horse, and landing mat. The reference strip of alternating 50cm black and white intervals was placed on each side of the approach strip. Two markers were placed on each side of the upper surface of the take-off board, 0.60m from the rear boundary. Six calibrations points (C1-C6) were utilised for the two high-speed stationary cameras, which recorded each vault. One panning camera filmed the approach for each trial from a raised platform.

Procedure

At the beginning of the testing session the gymnasts had their height and weight measured, and then completed their warm-up program. The gymnasts then completed five trials for each of the two experimental tasks, such that the gymnasts completed a total of ten experimental trials. The first experimental task was the performance of a round-off entry Yurchenko vault with a start value of at least 8.9, as governed by the International Gymnastics Federation Code of Points 2001-2004. Two elite level judges viewed the vaults from the side and provided a performance score for each vault. The gymnasts then completed a second task, which was an approach from the same distance as for the vault, with a round-off onto the board and a backward stretched salto onto landing mats. The landing mats were piled at the same
height, 1.25m, as the regular vaulting horse. No vaulting horse was utilised in the second task. The backward stretched salto was utilised to maintain the same level of difficulty between the vaulting task and the round-off salto task. No joint markers were utilised when filming the experimental trials. Due to the speed of the movement when vaulting, the skin shifts considerably, such that joint markers would not be accurate. It was also deemed not safe to place joint markers on gymnasts in such complex movements.

Design and Analysis

Videotape footage obtained from the panning camera was captured from a Sony DVCam DSR-20P VCR into computer format (*.avi file) using a Fast AV Master 2000 video capture card on a personal computer. The captured video footage was replayed field by field with the toe-off frame of each step digitised to obtain x,y coordinates of both the marker strip interval and the toe position. In addition, the wrists of both hands were digitised at hand contact. The x,y coordinate data for the toe at toe-off and the hands during ground contact of the round-off was then inputted into an Excel program to calculate step, hurdle and round-off length. From these time and position data the duration, frequency, and velocity of each step, the hurdle, and the round-off were calculated.

Visual control onset and the target perception threshold were identified consistent with experiments 1, 2, and 3. Further calculations were conducted to obtain the mean of the step, hurdle and round-off spatial and temporal data during the entire approach, the mean of the step, hurdle and round-off spatial and temporal data during visual regulation, as well as the velocity/time, acceleration/time, tau/time, and tau-dot/time profiles for the approaches.
Videotape footage of the vaults from the two stationary cameras was analysed to obtain three-dimensional x,y,z coordinates for fourteen points of the body, including the ankle, knee, hip, shoulder, elbow, and wrist for both the right and left side of the body, the vertex of the neck and chin, and the top of the head using APASWin 2000 software. The x, y, z coordinates for the fourteen points of the body were smoothed utilising a digital filter in APASWin2000 software. Ten frames prior to board contact and ten frames after landing were digitized to ensure no end effects during smoothing. From the three-dimensional position-time data for each vault, characteristics of the post-flight phase were measured to provide a kinematic profile for each vault. The kinematic post-flight measures included time, peak height, and landing distance from the edge of the vaulting horse. Videotape footage of the board contact phase was also viewed frame by frame to obtain the duration of the compression and repulsion components. Compression time was from the frame at which the feet contacted the board to the frame at which the upper surface of the board reached its lowest vertical displacement relative to the floor, i.e. maximum compression. The repulsion component was from maximum compression to the frame prior to the feet leaving the board. In addition, the duration of pre-flight and horse contact were also computed.

Linear regression was used to test relationships between dependent and independent variables, and multivariate analysis of variance with repeated measures (MANOVA, SPSS for Windows) was used to determine the significance of differences in approach characteristics between the two tasks. Two within-subject factors (Task 1&2) were entered into the analysis to determine the influence of the vaulting horse on the approach steps. The dependent variables of the approach,
Table 5.1. The types of vaults completed by the gymnasts, the start score for the vault, and the judge’s score. The start score provides a difficulty rating for each vault and is the maximum score that the performance can receive from the judge’s if completed with no errors.

<table>
<thead>
<tr>
<th>Gymnast</th>
<th>Trial</th>
<th>Vault</th>
<th>Start Score</th>
<th>Judge’s Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>4F1</td>
<td>1</td>
<td>Yurchenko Layout 360°</td>
<td>9.40</td>
<td>9.050</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Yurchenko Layout 540°</td>
<td>9.70</td>
<td>9.100</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Yurchenko Layout 720°</td>
<td>9.80</td>
<td>9.375</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Yurchenko Layout 720°</td>
<td>9.80</td>
<td>9.425</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Yurchenko Layout 720°</td>
<td>9.80</td>
<td>9.325</td>
</tr>
<tr>
<td>4F2</td>
<td>1</td>
<td>Yurchenko Layout</td>
<td>9.10</td>
<td>8.525</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Yurchenko Layout</td>
<td>9.10</td>
<td>8.350</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Yurchenko Layout</td>
<td>9.10</td>
<td>8.525</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Yurchenko Layout</td>
<td>9.10</td>
<td>8.450</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Yurchenko Layout</td>
<td>9.10</td>
<td>8.475</td>
</tr>
<tr>
<td>4F3</td>
<td>1</td>
<td>Yurchenko Open Tuck</td>
<td>8.90</td>
<td>8.275</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Yurchenko 180° Tuck</td>
<td>9.20</td>
<td>8.375</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Yurchenko 180° Tuck</td>
<td>9.20</td>
<td>8.625</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Yurchenko Tuck 360°</td>
<td>9.20</td>
<td>8.475</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Yurchenko Layout</td>
<td>9.10</td>
<td>8.475</td>
</tr>
<tr>
<td>4F4</td>
<td>1</td>
<td>Yurchenko Open Tuck</td>
<td>8.90</td>
<td>8.050</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Yurchenko Open Tuck</td>
<td>8.90</td>
<td>8.150</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Yurchenko Open Tuck</td>
<td>8.90</td>
<td>7.950</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Yurchenko Open Tuck</td>
<td>8.90</td>
<td>8.150</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Yurchenko Open Tuck</td>
<td>8.90</td>
<td>8.175</td>
</tr>
<tr>
<td>4F5</td>
<td>1</td>
<td>Yurchenko Open Tuck</td>
<td>8.90</td>
<td>8.025</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Yurchenko Open Tuck</td>
<td>8.90</td>
<td>8.025</td>
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<tr>
<td></td>
<td>3</td>
<td>Yurchenko Open Tuck</td>
<td>8.90</td>
<td>8.225</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Yurchenko Open Tuck</td>
<td>8.90</td>
<td>8.125</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Yurchenko Open Tuck</td>
<td>8.90</td>
<td>8.200</td>
</tr>
</tbody>
</table>

Average 9.14 8.476
kinematic performance measures of the vault, and the judge’s scores were correlated (Pearson’s r) to determine the strength and direction of any relationships.

Results

Judge’s Scores

The scores and difficulty rating for each of the vaults are shown in Table 5.1. The difficulty rating determines the start score, which means that a very difficult vault has a start score of 9.7 to 10.0, where as, an easier vault has a lower start score. It can be seen that gymnast 4F1 executed vaults of considerably greater difficulty than the other gymnasts. The performance scores ranged from 7.950 for a yurchenko open tuck through to a 9.425 for a yurchenko layout double twist. The judge’s scores reflected a good range of vaults for the two research questions on the approach and performance to be addressed.

Approach Characteristics

The approach in both of the gymnastics tasks comprised of three phases, as shown in Figure 5.4. An accelerative phase preceded a global visual control phase, where step lengths are adjusted to accommodate the position of the take-off board. A local visual control phase follows where step, hurdle, and round-off length adjustments are made to negotiate the take-off board for the required backward entry. Figure 5.4 also shows that the addition of the vaulting horse did not appear to qualitatively change the approach velocity or the timing of the three phases governing the control of the approach. The peak standard deviation of footfall positions (SOMax) for the entire approach, however, indicated greater variability in the approach characteristics for the non-vaulting task, 0.326m, when compared to the
Figure 5.4. The kinematic profile for the non-vaulting (a) and vaulting (b) tasks.

vaulting task, 0.214m. As shown in Table 5.2 there was an increase of 1.82% in approach velocity when vaulting, which was primarily due to increases in velocity during both the accelerative phase and the transition phase. Approach velocity
increased by 1.82% when the gymnasts completed their regular competition vaults, with the vaulting horse in place.

Table 5.2. The velocity during the key phases of the approach towards the take-off board when the gymnasts were vaulting and also when the vaulting horse was removed. Significant difference starred as follows, p≤0.05* p≤0.01**.

<table>
<thead>
<tr>
<th>Approach Section</th>
<th>Velocity (m/s)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vault</td>
<td>No Vault</td>
</tr>
<tr>
<td>Average Approach</td>
<td>5.52</td>
<td>(0.01)</td>
</tr>
<tr>
<td>Accelerative Phase</td>
<td>5.88</td>
<td>(0.49)</td>
</tr>
<tr>
<td>Visual Control Phase</td>
<td>4.86</td>
<td>(0.86)</td>
</tr>
<tr>
<td>Visual Control to Last Step</td>
<td>5.22</td>
<td>(1.85)</td>
</tr>
<tr>
<td>Hurdle to Board</td>
<td>4.98</td>
<td>(0.26)</td>
</tr>
</tbody>
</table>

As can be seen in Figure 5.5, the effect of approach velocity on visual regulation differed between the two tasks. When the gymnasts were not constrained by the vaulting horse, visual regulation decreased when approach velocity increased. In the vaulting task, visual regulation increased when approach velocity increased. Contrary to expectations, no significant task effects were found for the distance and time from the take-off board at which visual control onset emerged. On average the gymnasts approached the gymnastic take-off board over a 21.50m distance, of which 1.72s (41.85%) and 7.96m was visually regulated. A tau-margin of 1.27 described when visual regulation emerged for both tasks, as shown in Figure 5.6. Target perception defines the beginning of the local visual control phase, occurring earlier for
the vaulting task at 7.72m than for the non-vaulting task at 7.53m, when measured from the rear of the take-off board. The timing of target perception was consistent between tasks occurring 1.37s prior to board contact. The control of braking in target-

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**Figure 5.5.** The effects of approach velocity on the duration of visual control during the approach for the non-vaulting (a) and vaulting task (b).
directed locomotion is described by a tau-dot margin of $-0.54$. In the vaulting task an average tau-dot of $-0.28$ described the visual control phase, indicating greater braking adjustments during this phase when compared to the non-vaulting task tau-dot of $-0.26$. The tau-dot results for the two tasks reveals the additional constraint of the vaulting horse.

![Graph showing tau-time profile for vaulting and non-vaulting tasks.](image)

**Figure 5.6.** The tau/time profile for the vaulting and non-vaulting tasks.

In target-directed running there is a speed/accuracy trade-off, in which foot-placement accuracy decreases with increased approach speed (Bradshaw & Sparrow, 2000). In this experiment, there was the issue of foot placement position on the board. Ideally the gymnast utilizes the 0.60m half of the take-off board closest to the vaulting horse due to the greater return of potential energy from this section of the board. No differences were found between the two tasks in regards to foot placement position on the take-off board. In the non-vaulting task the toes of the feet were placed 0.77m
from the rear boundary of the board (closest to the approach strip), whereas the toes of
the feet were positioned at 0.80m in the vaulting task. When accounting for foot
length, the heels were, therefore, placed 0.17m for the non-vaulting task and 0.14m
for the vaulting task, from the forward boundary of the take-off board. Interestingly,
an interaction was found between approach velocity and the placement of the foot
during the hurdle. When approach velocity increased, foot distance of the hurdle from
the rear boundary of the board increased \( (r=0.489, p\leq 0.01, y=0.4394x^3-
6.5088x^2+31.82x-45.784, R=0.78) \), which enabled the gymnast to accommodate the
increased approach velocity and still land onto the board in the correct position for
take-off. The interaction between approach velocity and the hurdle position, as well as
the foot-positioning accuracy on the board confirms that a speed/accuracy trade-off
does not govern the control of the approach to the board.

Vaulting Performance and Judge's Score

Increased velocity during the visual control phase of the approach in
yurchenko-entry vaulting was found to significantly increase post-flight time
\( (r=0.555, p<0.01) \), height \( (r=0.497, p<0.01) \), and distance \( (r=0.660, p<0.01) \). In
addition, as shown in Figure 5.7, the judge's score \( (r=0.765, p<0.01) \) increased with
higher approach velocity during the visual control phase of the approach. No
significant relationship was found between the velocity during the accelerative phase
of the approach and either post-flight characteristics or performance scores. Average
approach velocity, however, was related to judge's score \( (r=0.683, p<0.01) \). The
results confirmed, therefore, that approach velocity during the visual control phase is
directly related to post-flight performance and judge's scores.
Figure 5.7. The effect of approach velocity during the visual control phase when vaulting on post-flight distance (a) and judge’s score (b).

As revealed in Table 5.3, the pre-requisites for a high velocity approach was an earlier onset of visual control with respect to distance ($r=0.830$, $p<0.01$), footfalls ($r=0.824$, $p<0.01$), and time ($r=0.776$, $p<0.01$). Visual regulation increased linearly with respect to distance ($r=0.816$, $p<0.01$; $y=12.231x-59.961$, $R=0.80$), and time
(r=0.846, p<0.01; y=1.8054x-8.3221, R=0.84) to the rear boundary of the take-off board, enabling faster approach velocity.

Table 5.3. Visual control onset characteristics, distance to the board, the number of steps prior to the hurdle (H) step (S) round-off (R) phase, and time as a percentage of total approach time. Also included is the average velocity during the visual control phase, the hurdle to board velocity, post-flight time during vaulting performance, start and judge’s score.

<table>
<thead>
<tr>
<th>Gymnast</th>
<th>Visual Control</th>
<th>Hurdle to</th>
<th>Post-Flight</th>
<th>Start</th>
<th>Judge’s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dist. (m)</td>
<td>Steps (n)</td>
<td>Time (%)</td>
<td>Vel. (m/s)</td>
<td>Board Vel. (m/s)</td>
</tr>
<tr>
<td>1</td>
<td>17.20</td>
<td>6</td>
<td>77.74</td>
<td>5.98</td>
<td>5.31</td>
</tr>
<tr>
<td>2</td>
<td>6.71</td>
<td>1</td>
<td>36.77</td>
<td>5.10</td>
<td>5.26</td>
</tr>
<tr>
<td>3</td>
<td>5.39</td>
<td>H</td>
<td>29.18</td>
<td>4.94</td>
<td>4.94</td>
</tr>
<tr>
<td>4</td>
<td>6.84</td>
<td>1</td>
<td>37.01</td>
<td>4.86</td>
<td>4.81</td>
</tr>
<tr>
<td>5</td>
<td>3.08</td>
<td>S</td>
<td>28.26</td>
<td>3.41</td>
<td>4.82</td>
</tr>
<tr>
<td>Mean</td>
<td>7.83</td>
<td>1</td>
<td>41.79</td>
<td>4.86</td>
<td>4.98</td>
</tr>
</tbody>
</table>

A high approach speed is essential for the performance of very difficult vaults. The affect of approach speed on vaulting performance and judge’s score is summarised for the highest and lowest scored vault from the current experiment in Figure 5.8. Characteristic of increased approach speed, the hurdle increased in length (r=0.705, p≤0.01) and duration (r=0.663, p≤0.01), but not in velocity. The round-off
Figure 5.8. Measures of the approach and vaulting performance for the highest and lowest score. VC denotes visual control. Significant correlations with approach velocity starred $0.05*/0.01**$. 
lengthens ($r=0.456$, $p \leq 0.05$) but decreases in duration ($r=-0.614$, $p \leq 0.01$) with a faster approach, thus, increasing in velocity ($r=0.686$, $p \leq 0.01$).

The second phase of the round-off is from hand push-off to board contact. The position of the hands with respect to the rear boundary of the board decreased in distance ($r=-0.663$, $p \leq 0.01$) with an increase in approach velocity. The shortening of the second phase of the round-off produces a quicker "snap-down" component to the second phase of the round-off. The compression section of board contact was unrelated to approach velocity; however, the repulsion section was shorter in duration ($r=-0.651$, $p \leq 0.01$) when approach velocity increased. A short repulsive board contact time resulted in increased post-flight time ($r=-0.405$, $p \leq 0.05$) and thus performance score ($r=-0.592$, $p \leq 0.05$).

**Discussion**

In both experimental tasks the gymnasts were required to run as fast as possible and complete a round-off onto the take-off board. The movement of the gymnast changes from a forward running movement to a backward movement during the transition phase of the hurdle step round-off. The gymnast, when vaulting, then negotiates a second obstacle, the vaulting horse. Interestingly, the approach speed slowed when the vaulting horse was removed. One explanation for this pattern is that the second task could be considered novel to the gymnasts, as they would rarely practice the task of completing a round-off onto the take-off board with a stretched backward salto from such a long running approach distance. A related task that is well practiced by gymnasts is a round-off entry beam mount. In this type of beam mount the gymnast typically approaches the take-off board from a distance of approximately 5m, completing movements such as a backward stretched salto (airborne rotation in
the sagittal plane) onto the beam as the start of an acrobatic series. The control of braking during the visual control phase, however, revealed that greater braking occurred when the approach was constrained by both the take-off board and vaulting horse.

An increase in approach velocity was directly related to the judge’s score, consistent with previous research in the literature concerning vault approach velocity (e.g. Bruggemann & Nissen, 1981; Krug, Knoll, & Zocher, 1998). The major component of increased approach velocity was the ability of the gymnast to commence visual regulation earlier in the approach. When visual regulation occurred earlier, smaller progressive adjustments to step length occurred, enabling the gymnasts to be able to accommodate the hurdle-step-round off onto the take-off board with attenuated affects on approach velocity. The velocity during the visual control phase of the approach was directly related to the post-flight performance measures and judge’s score.

A three-phase pattern governed the control of step length during the approach for the two tasks when performed by the gymnasts, indicating that the two-phase pattern in experiment 2 for a forward entry running approach towards a take-off board was due to the limited experience of the performers utilized. An interaction was found between approach velocity and hurdle position. When approach speed increased, the hurdle to board distance increased. The interaction between the hurdle position and approach velocity enabled the gymnasts to land in a consistent position on the take-off board, regardless of approach velocity. A speed/accuracy trade-off, therefore, does not govern the control of the approach towards the gymnastic take-off board for gymnasts, otherwise known as expert performers, and also in novice performers, as examined in experiment 2. The observed consistency in foot position on the take-off
board appears to be due to the 0.60m useable target length of the take-off board, as previously stated in experiment 2, which is above the cut-off point for constraint by a target on the approach run.

The consistency of foot placement during each step during the approach decreased when the gymnasts completed the novel running task. Furthermore, when comparing the peak standard deviations of the non-vaulting task of the gymnasts (0.326m), to that of the novice performers in experiment 2 (0.288m) when sprinting towards the take-off board, it can be seen that consistency of foot placement decreases with increased approach distance. Regardless of approach distance, however, consistency of foot placement increases with task experience, demonstrated in the vaulting task of the expert performers (0.214m).

![Figure 5.9. The magnitude of timing error in novice and expert performers.](image)

In experiment 1 and 2 the timing error, that is, the time to contact estimates (tau) in comparison to the measured time to contact, was examined for the
accelerative phase. It was suggested that the high magnitude of timing error during the accelerative phase of the approach was related to gait initiation and also accounted for the delayed regulation of step length at high approach velocities. Experience is a mediating variable in the observer's ability to visually control step length during target-directed locomotion. The magnitude of timing error in time to contact judgements for novice and expert performers is revealed in Figure 5.9. In Figure 5.9, the time to contact judgements (tau) are presented as a percentage of measured time to arrival for the sprinting approach towards the take-off board in novice performers and the approach towards the take-off board and vaulting horse in expert performers. Novice performers generally overestimated time to contact with the take-off board, probably allowing a large safety margin for judgement error. Expert performers, however, slightly underestimated time to contact with the take-off.

In summary, the results demonstrated that when step length regulation occurred earlier during the approach towards the take-off board and horse in yurchenko vaulting, approach velocity increased and vaulting performance increased as indicated by the judge's score. With high levels of practice, visual regulation increases with approach velocity during the running approach towards the take-off board. The skill of expert performers is, therefore, partly due to their ability to visually regulate for a greater time and distance during the approach when approach velocity increases, allowing smaller and systematic step length adjustments to be executed, resulting in accurate final foot placement when negotiating the take-off board.

Recommendations for training include the early inclusion of different targeting activities whilst running, such as that seen in long jumping and hurdling, and completing vault timers from different approach distances. Biomechanical feedback
can also provide valuable information on whether extra target-directed running drills are improving the visual regulation pattern during the approach when vaulting. Whilst the approach towards the take-off board has been investigated for novice performers, further research is needed to determine the pattern governing step length regulation in forward entry vaults for elite gymnasts, including the effects on vaulting performance. The approach towards the take-off for beam mounts could also be investigated in regards to the approach step length characteristics for forward and backward entry mounts, with and without the beam, as well as unconstrained running over the same approach distance.
Chapter 6

Summary and Discussion
The optic array generated at the eye between the movement of the observer and the surface elements of a target (affordances) reveals the necessary information for the guidance and control of locomotion. The act of adjusting the timing and length of each step is, therefore, a visual and a muscular action (Gibson, 1958). The observer’s state of motion as characterized by the mode of locomotion, often the speed of locomotion, and gender (mediating variables) affects the utilization of visual stimulus. In addition, the experience of the observer plays an important role in the capacity to utilize visual stimulus to control the muscular action of locomotion when either maintaining or adjusting the step mechanics.

The optic array generated through the observer’s movement is unique to the target and the environmental surroundings. The terrain, that is, the ground or floor surface, reflects light in a manner consistent with the regularities or irregularities of the surface. Through the visual and kinesthetic senses, the observer can adjust locomotion to accommodate the surface encountered. When a surface is slippery, for example, the observer will sense the low frictional forces during ground contact of the foot. The characteristics of the target (the affordance), such as spatial definition and the boundaries affect the pattern of the optic array generated. The optic array generated enables the target to be visually perceived, so that the observer can adapt the locomotor pattern to safely negotiate the target. The number of boundaries defining a target or the height of a raised surface, for example, affects the observer’s action.

When walking towards a roadside kerb to cross a busy intersection, locomotion is controlled to enable the observer to stop. When running towards a gymnastic take-off board, however, the observer maintains approach velocity to enable the execution of the resulting movement. The control of braking based upon
the visual and muscular action, therefore, depends upon the type of collision with the target. The action criterion also determines the observer’s movement. In everyday locomotion such as when approaching a set of narrow descending stairs the action criteria is to avoid harm. In sporting locomotion such as a long jump approach, the action criterion is to maximize performance. In target-directed locomotion, the observer adapts the visual and muscle action to accommodate the specific criteria of the task based upon prior experience.

A speed/accuracy trade-off governs the visual control of highly constrained target-directed locomotion. When foot-placement is highly constrained by a target, the approach slows. A decrease in approach velocity prolongs visual regulation of step length and duration, leading to accurate final foot-placement with the contingency to be negotiated, such as a narrow target or the edge of a set of descending stairs. An upper limit exists for the spatial constraint of a target that will induce the speed/accuracy trade-off mechanism.

In target-directed walking, Drury and Woolley (1995) estimated that targets above 30cm in length would not sufficiently constrain locomotion to warrant visual regulation of step length. When the visual regulation of step length whilst walking towards a target was examined in experiment 1, the average target length that was placed in the participants’ path was 32cm in length. The approach kinematics for target-directed walking revealed that 62% of the 10m-approach distance was visually regulated, suggesting that possibly targets up to 35cm in length would still induce visual regulation in walking and, also, a speed/accuracy trade-off mechanism.

In target-directed running Bradshaw and Sparrow (2000) suggested that a target length greater than approximately 57cm would not induce a speed/accuracy trade-off. In gymnastics vaulting, examined in experiment 4, the gymnast aims to
utilize the 60cm half of the take-off board closest to the vaulting horse and landing mats due to the greater return of potential energy from this section of the board. No evidence was found to imply that a speed/accuracy trade-off governs the approach towards a gymnastic take-off board, supporting the suggested upper limit of 57cm for target constraint by Bradshaw and Sparrow (2000).

The lack of a speed/accuracy trade-off mechanism governing the approach towards a target, however, does not imply that there is no visual regulation of the timing and length of the steps. Visual regulation of the approach run towards the gymnastics take-off board, for example, was found in both novice and expert performers. The spatial constraint of a double-boundary target is only one example of a targeting task, which can induce visual regulation of step length. Visual regulation was also exhibited in the kinematics for approaches towards a single-boundary target, a raised surface, and a raised rod.

The examination of the final stride in a hard impact with the targeting tasks revealed that the placement of the foot prior to the target increases in distance with higher approach speed, enabling accurate final foot placement across a range of approach speeds. For example, when approaching a raised surface it was found that the final step onto the platform increased in length with higher approach velocities. Thus, the interaction between foot placement prior to the target and approach speed enables consistent final foot placement, without the control of a speed/accuracy trade-off mechanism in other related hard impact targeting tasks. In soft impacts with targets there was no interaction between placement of the foot prior to the target and approach speed. The foot was placed consistently 0.54m prior to the target, enabling accurate final foot placement with zero velocity. The final foot placement prior to the target is a determinant for successful target negotiation.
The approach towards a target is governed by three distinct phases. An accelerative phase precedes a global visual control phase where the timing and length of each step was adjusted to accommodate the position of the target and to control the velocity of the approach. Finally, a local visual control phase governs the control of the step kinematics to negotiate the target with accurate final foot-position. The type of collision with an obstacle, hard or soft, does not affect the duration of visual regulation of the whole-body approach. Consistent with Bradshaw and Sparrow’s (2000) study of target-directed running, the accelerative phase is ballistic in the soft-impact task. The increased movement time for the soft impact task is due to a greater proportion of time adjusting the timing and length of each step during the local visual control phase, to enable accurate final foot-placement with zero final velocity.

Visual regulation emerged earlier for slower modes of locomotion. When walking, visual regulation commenced at an average tau margin of 3.41, resulting in 4.08s of the approach being visually regulated. The amount of visual regulation, therefore, decreased when jogging ($\tau_m=1.61/T=2.11s$) and running ($\tau_m=1.08/T=1.64s$). Interestingly, the tau margin of 1.08 that describes the visual regulation of running is consistent with the results of Laurent, Tornadore, and Bovet (1987), who found a tau margin of 1.03. Visual regulation in hard impact target-directed locomotion commences earlier at slower approach velocities. In the soft-impact target-directed running, however, there was no evidence of an approach velocity affect on visual regulation.

The subsequent examination of expert performers in gymnastics revealed that the pattern governing visual regulation across different approach velocities in hard impact target-directed gait tasks is characteristic of novice performers. In expert performers, visual regulation commences earlier at high approach velocities, leading
to increased sporting performance. An essential building block for successful performance in gymnastics vaulting is a high-velocity approach towards the take-off board. The gymnast’s ability to visually regulate the approach is a pre-requisite for the performance of very difficult vaults, as it enables the take-off board to be negotiated with small and systematic adjustments to the timing and length of each step, in order to minimize the decrements to approach velocity. Aptitude of expert performance in gymnastics vault is, therefore, due to the ability of the gymnast to increase visual regulation of step length at higher approach velocities.

The magnitude of timing error during visual regulation further revealed the effect of task experience when visually regulating step length towards a target. The novice observer generally overestimates time to contact with targets in the environment, possibly allowing a large safety margin for perceptual error in time to contact judgements. The magnitude of timing error in perceptual judgements of the experienced observer, however, is relatively low. The effect of experience on timing error underlies the observer’s ability to visually regulate step length, particularly when controlling braking to safely negotiate the target.

The visual control of braking in target-directed locomotion was governed by a tau-dot margin of −0.54. The braking adjustments in locomotion is, therefore, similar to the braking adjustments of mechanical systems, such as braking when driving an automobile, which is governed by a tau-dot margin of −0.50. The capacity of the human body to brake during locomotion is therefore similar to that observed in automobile braking tasks. Furthermore, it is possibly physically improbable for the human body to brake during locomotion at a tau-dot margin greater than −0.7 without harm. Target constraint was also reflected in the tau-dot margin, with greater braking observed when approaching a narrow target. The braking adjustments were also
greater when approaching more than one obstacle, the take-off board and vaulting
horse, then when approaching a single obstacle, the take-off board only.

In target-directed locomotion the forward boundary of the target is utilised as
the key guide for positioning the foot within the target. The utilization of the toe in
foot-placement further illustrates the use of vision, as the observer would need to
rotate the head to visually guide the placement of the heel, a tactic that was not
observed for any of the participants in the current study. The accuracy of foot-
placement when required to position the foot utilising the heel, therefore, is completed
with low spatial accuracy. The guidance of foot-placement to negotiate targets is
guided principally utilising the toe.

The guidance of final foot-placement with a target that comprises a height
component is affected by the observer’s gender. A possible behavioral process
underlies the safety-margin observed in female observer’s final foot placement, that
provides scope for judgment error. When the female observer approaches a raised
rod, for example, the rod is crossed allowing for greater toe clearance. Similarly,
when placing the foot on a raised surface, the female observer allows a large safety
margin for error, placing the foot closer to the forward boundary as opposed to the
critical (hazardous) rear boundary.

In conclusion, information-based regulation of locomotion to control step
placement begins when the circumstances require it, that is, locomotion is controlled
within a world of perceived surfaces. People adapt target-directed gait to
accommodate the specific target image (affordances) such as the spatial constraint of
the target, based upon the mediating factors of gait mode, whole-body approach
velocity, gender, and experience. In the everyday environment the main performance
criterion is to avoid harm, where as in the sporting environment, such as in
gymnastics vaulting, the main criteria is to maximize performance. Expert performers are capable of increasing visual regulation at higher approach speeds; however, in everyday walking tasks and novel running tasks, visual regulation of step length decreases when approach speed increases. Future research suggestions include investigations concerning the visual regulation of foot-placement in curved target-directed locomotion and visual regulation towards obstacles across a variety of approach distances. The control of braking in both biological and mechanical systems, such as the control of gait in children could also extend the current knowledge of direct perception and the control of movement, further testing the robustness of the tau-dot margin of −0.5. The sport of long jumping also warrants further attention to measure the effectiveness of run-through training (the approach without the jump) by examining the approach pattern when completing run-throughs and when completing the jump. An in-depth examination of the approach and long jump performance in a similar method to the gymnastics vaulting experiment, at the start and end of the domestic competition season, could also provide further knowledge of this athletic skill with significant training implications.
References


Appendices
Appendix 1: Spatial reference system

The spatial reference system utilised in the current study, defines Y as movement in the vertical (upwards-downwards) direction, X as movement in the anterior-posterior (forwards-backwards) direction, and Z as movement in the medial-lateral (sideways)

Figure A1.1. The spatial coordinate system utilised for the three-dimensional data collection and analysis (adapted from Martini, 1998).

direction (Figure A1.1). The derivatives of X, Y, and Z are the velocity of the movements in those directions, defined as \( \dot{X} \), \( \dot{Y} \), and \( \dot{Z} \). When velocity of the movement in any of the
\( \dot{X}, \dot{Y}, \text{ and } \dot{Z} \) directions is increasing, the convention is positive. The derivatives of \( \dot{X}, \dot{Y}, \) and \( \dot{Z} \) are the acceleration of the movements in those directions, defined as \( \ddot{X}, \ddot{Y}, \text{ and } \ddot{Z}. \)
Appendix 2: Derivation of the tau (τ) strategy in the control of movement towards a target (from Lee, 1976).

Figure A2.1. (a) Anatomy of the eye, illustrating the lens and retina. The nodal point of the eye is through the visual axis. (b) An observer approaching a target at time t. The movement of the point of observation (O) relative to the environment generates an optic flow field in the direction of Z to 0. P (Target) and G (ground) denote texture elements in the environment. Light is reflected from the moving environmental texture elements passes through the nodal point of the lens of the eye, giving rise the optic texture elements P' and G' on the retina (from Lee, 1976).
Figure A2.1 represents Lee’s (1976) model for the perception of time to contact with a target placed at eye level. First, note that there is a radial flow line (locomotor flow line) between the observers eye and the horizontal element Z of the target. It is from the radial flow line that the observer can perceive time to contact prior to the target perception threshold, where the size of the target can be judged.

Position of Element P (Relative to the Eye)

The position of element P is defined by the radial flow line Z(t) and R, the size of the target, and the angle between the OZP and OZX planes (angle between triangles hypotenuse and the horizontal plane). The optical specification of the environmental relationship between Z(t) and R is as follows:

\[ \frac{Z(t)}{R} = \frac{1}{r(t)} \] ........................(1)

In this equation the target is viewed as an image (much like a camera does) as it is missing depth from the equation. The equation defines the position of the target (direction), providing no information on the distance of the target from the observer.

Spatio-Temporal Structure of the Optic Flow Field from Element P

To gain the spatio-temporal structure of the target in the observers view, equation (1) must be differentiated with respect to time.

\[ \frac{R}{V} = \frac{r(t)^2}{V(t)} \] ........................(2)
where \( V = -dZ(t)/dt \), the velocity of the eye relative to the environment, and \( v(t) = dr(t)/dt \), the velocity of the optic texture element \( P' \), the optic representation of the target.

Eliminating \( R \) between equations (1) and (2) yields:

\[
Z(t)/V = r(t)/v(t) \tag{3}
\]

where \( Z(t)/V \) is the environmental specification of time to contact, and \( r(t)/v(t) \) is the optical specification.

Judging Target Height and Width in Locomotion

When walking or running towards a stationary target in the immediate environment, there is also the problem of distance and size perception. Lee's (1980) model indicated that available in the optic flow field at the eye is information about relative sizes and distances of a target in environment, scaled in terms of the observers velocity, height, and step length.

Using Height (\( H \)) for Distance Perception

In Figure A2.1, \( H \) is the R-coordinate of any texture element on the ground over which an observers eye will pass. Applying equation (2) to the ground texture element \( G \), derives the following equation:
\[ \frac{H}{V} = \frac{r_g(t)}{V_g(t)} \] .......................... (4)

Eliminating \( V \) between equations (2), (3), and (4) yields:

\[ \frac{R}{H} = \frac{r(t)}{v_g(t)} \frac{r_g(t)}{v(t)} \] .......................... (5)

\[ \frac{Z(t)}{H} = \frac{r(t)}{v_g(t)} \frac{r_g(t)}{v(t)} \] .......................... (6)

Using Step Length (L) and Duration (t_d) for Distance Perception

L is the length of the observer’s steps. The distance remaining to the target can be calculated as follows:

\[ Z(t-t_d) - Z(t) = L \] .......................... (7)

Thus from equation (3) and \( \tau(t) = \frac{r(t)}{v(t)} \):

\[ \frac{[Z(t-t_d) - Z(t)]}{V} = \frac{L}{V} = \frac{\tau(t-t_d) - \tau(t)}{\tau(t)} \] .......................... (8)

Eliminating \( V \) between equations (2), (3), and (8):

\[ \frac{R}{L} = \frac{r(t)\tau(t)}{\tau(t-t_d) - \tau(t)} \]

\[ = \frac{r(t)\tau(t)}{t_d} \] .......................... (9)
\[ Z(t)/L = \tau(t)/[\tau(t-t_3)-\tau(t)] \]
\[ = \tau(t)/t_3 \] \hspace{1cm} (10)

*Judging Target Height or Width*

Lee (1980) omitted from the calculations for time to contact and distance judgements, how an observer judges target characteristics such as height or width. Lee (1980), however, did mention that height of a target, such as a hurdle, could be body-scaled, that is, judged as a proportion of body height.

\[ \text{Height Perception} = \frac{\text{Target Height}}{\text{Body Height}} \] \hspace{1cm} (11)

Similarly, target width in the anterior-posterior direction could be judged as a proportion of the observers step length.

\[ \text{Width Perception} = \frac{\text{Target Width}}{\text{Step Length}} \] \hspace{1cm} (12)

Alternatively, target width could be judged using foot length as the reference scale, which would be particularly relevant during final foot placement with the target.

\[ \text{Width Perception} = \frac{\text{Target Width}}{\text{Foot Size}} \] \hspace{1cm} (13)
Appendix 3: Derivation of $\dot{\tau}$ in the control of braking.

Lee (1976) demonstrated that $\tau$ and $\dot{\tau}$ can be calculated at any point in time during visual regulation from the distance ($Z$), velocity ($\dot{Z}$), and acceleration ($\ddot{Z}$). The model proposes that time-to-contact ($\tau$) can be optically perceived from the optical expansion rates between an observer (O) at a distance ($Z$) from the obstacle of size ($S$) at a particular point in time (t). The inverse rate of dilation of the visual angle ($\Theta$) with the obstacle specifies the current distance and velocity of the observer at a given time during the approach, thus corresponding to current time-to-contact ($T_c$ or $\tau$) with an obstacle (Bardy & Warren, 1997). The optical quantity of time-to-contact is calculated as follows:

$$\tau(t) = \frac{\dot{\Theta}(t)}{\Theta(t)} = \frac{\dot{Z}(t)}{Z(t)} = T_c(t) \quad \text{..........(1)}$$

The rate of change of time-to-contact (Bardy & Warren, 1997), yields information on the pattern of acceleration and deceleration exhibited when controlling movement.
The rate of change of tau (τ) is known as tau-dot (τ̇) and is calculated by differentiating equation 1.

\[ \tau(t) = \frac{Z(t)}{\tilde{Z}(t)} \] ...........(1)

\[ \dot{\tau}(t) = \frac{d\tau}{dt} = \frac{d}{dt} \left( \frac{Z(t)}{\tilde{Z}(t)} \right) \]

\[ \ddot{\tau}(t) = Z \times \frac{d}{dt} \left( \frac{1}{\tilde{Z}} \right) + \frac{1}{\tilde{Z}} \times \frac{d}{dt} \left( Z \right) \]

\[ \ddot{\tau}(t) = Z \times \left( -\frac{1}{\tilde{Z}^2} \frac{dZ}{dt} + \frac{1}{\tilde{Z}} \frac{d}{dt} \left( -\tilde{Z} \right) \right) \]

\[ \dot{\tau}(t) = -\frac{ZZ}{\tilde{Z}^2} \]

\[ \dot{\tau}(t) = -\left( 1 + \frac{ZZ}{\tilde{Z}^2} \right) \] ...........(2)

When tau is defined with a negative distance such as by Bardy and Warren (1997), shown in equation 3, the calculation for tau-dot is as follows:

\[ \tau(t) = -\frac{Z(t)}{\tilde{Z}(t)} \] ...........(3)

\[ \dot{\tau}(t) = \frac{ZZ}{\tilde{Z}^2} - 1 \] ...........(4)
Appendix 4: Video and computer hardware considerations

The video and computer hardware used in the current study will be described here prior to a detailed description of the error measurements obtained for the gait analysis protocol (Appendix 5). During the course of the project, digital video equipment was made available, which was first used in experiment 3. First, types of video cameras used in the study will be described prior to an overview of the process by which a video image is produced according to the video format in Australia.

Video Cameras

Two types of 50Hz video cameras were utilised in the current study. A Super VHS Panasonic MS4 camera was employed during experiments 1 and 2, whilst a Sony Digital DSR-200AP camera filmed during experiments 3 and 4. Super VHS and Digital camera technology will therefore be explained.

Super VHS technology differs to VHS technology in the picture quality of the video image. Super VHS consists of two separate signals called the chrominance and the luminance. The chrominance is the colour signal that is made up of hue (colour) and saturation (vividness). Luminance is the brightness of the picture, which is determined by the electrical intensity of the image. The advantage of the two signals being separate is that it eliminates cross talk and interference between the two signals. The result is a more resolute picture with better colour. In Super VHS format, later reproductions such as when captured onto a computer, are of a higher quality than VHS of the same generation.

Digital camera technology is similar to Super VHS technology; however, the video signals are processed digitally as opposed to the old analogue format. In digital recording format there is also two separate signals, chrominance and luminance. The
digital processing increases the stability of the signals resulting in greater picture quality. In the current study this provides a further advantage in that the digital signal is compatible with computers. When capturing video onto a computer, which will be described later, the video signal does not have to be converted from analogue to digital format. The quality of video in captured form on a computer is greater as no frames of the video are lost during the process. The main disadvantage of standard video cameras is the low field rate of 50Hz. A good quality video capture card can view each field separately, however, for high-speed actions the clarity of the picture is still poor. In the last experiment of the current study, the speed of the post-flight phase of the gymnastics vaulting was too fast for a standard video camera.

The high-speed camera system utilised in Experiment 4 was the Redlake Motionscope PCI500 that can capture images up to 1000Hz (500fps). The PCI-based system operates through a computer capturing up to 8 seconds of movement when operating at 50fps. The advantage of a PCI-based system is that multiple cameras can be synchronized in relation to the fields (odd or even) during filming, and the trigger function that can activate multiple cameras synchronously. A pre-trigger function enables the collection of video footage to be triggered at the end of a movement. For example, recording in experiment 4 was triggered at the completion of the gymnastics vault, so that the video images saved included the video footage prior to the trigger, thus, the actual vaulting movement. As the video footage is captured directly into computer format at the time of filming, no video capture card is required to convert the video footage into computer format. The film and shutter speed considerations, however, and the video capture hardware will be outlined as they apply to the series of experiments.
The Australian Format for the Production of Video Images

Each of the 50Hz video cameras utilised contain three small CCD (Charge Coupled Device) chips. Each CCD chip converts light into an electrical signal by collecting charge onto an array of photodiode elements. The amount of charge collected on the photodiode elements is proportional to the amount of light falling upon it. Each of the CCD chips pick up a separate primary colour (red, green, or blue), which in turn improves the chrominance of the image. Chrominance is the colour and vividness of the image. The charges collected by the CCD chips are transferred line by line through a vertical and then horizontal register. The PAL (Phase Alternate Line) format causes these lines to be scanned separately, odd numbered lines first, then even numbered lines, totalling 625 lines. Two separate fields are produced, an ‘odd’ field and an ‘even’ field, which interlace to form a single frame. The rate at which each field is scanned is dependent upon the frequency of electrical power, which is 50Hz in Australia. Thus, the operating frequency for the 50Hz video cameras utilised in the current study was 50 fields (25 frames) per second.

Video Settings, Video Capture and Other Computer Hardware Considerations

The field of focus in the locomotion aspect of the experiments was normal. As will be reviewed in the following section on the gait analysis procedures, the camera was panned from an elevated platform adjacent to a horizontal approach strip. The field of focus enabled approximately 1.5-2.0m of the approach strip to be filmed at any moment in time, therefore, the f-stop setting which determines the amount of light entering the lens, was at a medium setting. The shutter speed, the exposure time of the film, was set at 1/500s, enabling clear field-by-field filming of the gait pattern. Four camera lights were placed along the side of the horizontal approach strip, outside of
camera view, to provide enough light for the filming of the movement. Prior to each filming session, the 50Hz video camera was white balanced. White balancing is performed to show the camera what white represents in the current lighting conditions and ensures accurate representation of all other colours in the image. As the experiments were conducted in indoor settings with heavy black curtains covering all windows, the lighting conditions were controlled so that the lighting conditions did not change during the filming session.

The field of focus in the gymnastic aspect of the last experiment was wide. A wide lens was utilised to enable the two stationary high-speed cameras to each view approximately 10m of space in the horizontal plane, and approximately 4m of space in the vertical plane. As will also be reviewed in greater detail in a later section, the high-speed cameras were placed in stationary positions, oblique-right and oblique-left to enable three-dimensional filming and analysis of the gymnastic vaulting movement. As the field of focus was wide, the f-stop setting was low, to enable plenty of light during filming. The speed of movement in gymnastic vaulting is fast. A typical vault lasts only 1.2s; therefore, the movement was filmed at 250Hz with a shutter speed of 1/1000s. Two camera lights were placed outside of camera view, adjacent to the filming area to provide enough light for filming. An extra consideration when placing the camera lights was also to ensure that the lights did not directly shine into the eyes of the gymnast when vaulting. The two cameras were genlocked to ensure synchronized filming (field by field) between the two cameras. A pre-trigger of 100% was utilised to activate recording.

Aside from the video technology and required settings when filming the experimental sessions for the four experiments were the computer hardware and software considerations for the analysis of the video footage. A Fast AV Master 2000
video capture card was utilised on a Windows 98 personal computer. The colour resolution of the video capture card is 24-bit true colour and the geometric resolution is 768*576 pixels for PAL format. An advantage of the Fast AV Master 2000 video capture card is that it can playback video footage field by field, providing the aptitude for more detailed and accurate analysis. A 17 inch Mitsubishi Diamond Plus 71 colour monitor was utilised during film analysis, which has a horizontal and vertical resolution of 1280dots * 1024 lines. The video footage was played on either one of two video tape recorders (VTR), depending on the camera utilised during data collection. When the experiment was filmed using a Super-VHS video camera the video footage was played back on a Grundig GV 690 VTR during the video capture process. When the experiment was filmed using a digital video camera, the video footage was played back on a Sony DVCam DSR-20P VTR. The data analysis process will be described in the following sections. In-house two-dimensional video analysis software was utilised to analyse the locomotion aspects of the experiments in conjunction with custom written software in Microsoft Excel. Ariel Dynamics APASWin 2000 software was utilised to analyse the gymnast vaults in experiment 4 three-dimensionally. The data collection and analysis of the locomotion aspects of the experiments will now be described in greater detail to explain the development of the gait analysis protocol, together with the accuracy of the measurements gained.
Appendix 5: Gait analysis protocol: Step length and duration measurement

An accuracy test was conducted for a 10m approach utilising the experimental set-up for the first three experiments, as shown in Figure A5.1. The 1.22m wide approach strip was marked utilising two 0.05m parallel lines with alternating black

![Diagram showing a 10m approach strip with a target and filming platform.]

Figure A5.1. The typical experimental set-up for the first three experiments of the current study, consisting of a 15m approach strip marked with two parallel lines. The parallel lines consisted of alternating 0.50m black and white intervals. One 50Hz video camera panned and filmed from a platform adjacent to the approach strip.

and white intervals. One 50 Hz panning video camera was placed on a platform adjacent to a 15m-approach strip. A typical field of video footage is shown in Figure A5.2. Toe to target distance and, thus, step length measurements were gained by digitising the video footage and then using the x,y coordinates as input into a custom written Microsoft Excel program, together with the marker intervals analysed. The order of digitization is also shown in Figure A5.2, including the toe, posterior and anterior markers.
Figure A5.2. A typical field in the video footage of the current series of experiments, showing the order of digitization.

In the accuracy test conducted on the experimental set up for the current experiment, the toe-to-board distance and step length measurement errors were obtained. Ten white cardboard footprints were placed at known distances along the 10m-approach strip. As can be seen in Table A5.1, the average measurement error for toe-to-target distance was $\pm 0.35\text{cm}$ and $\pm 0.30\text{cm}$ (0.4% error for step lengths of 0.8m, 0.2% error for step lengths of 1.50m) for step lengths. The measurement errors obtained for the gait analysis protocol was deemed acceptable when compared to the to the literature for similar gait analysis protocols. Hay (1988), for example, reported a measurement error of $\pm 0.5\text{cm}$ for toe-to-board and step length measurements. Furthermore, the measurements errors obtained compare favourably to two-
Table A5.1. Digitization error in the toe-to-target distance and step length measurements for the current experiment.

<table>
<thead>
<tr>
<th>Footfalls to the Target (n)</th>
<th>Toe-to-Target Distance Measured (m)</th>
<th>Toe-to-Target Distance Digitised (m)</th>
<th>Absolute Digitising Error (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>10.000</td>
<td>9.996</td>
<td>0.400</td>
</tr>
<tr>
<td>6</td>
<td>8.280</td>
<td>8.278</td>
<td>0.200</td>
</tr>
<tr>
<td>5</td>
<td>6.550</td>
<td>6.553</td>
<td>0.300</td>
</tr>
<tr>
<td>4</td>
<td>5.090</td>
<td>5.094</td>
<td>0.400</td>
</tr>
<tr>
<td>3</td>
<td>3.430</td>
<td>3.438</td>
<td>0.800</td>
</tr>
<tr>
<td>2</td>
<td>1.920</td>
<td>1.923</td>
<td>0.300</td>
</tr>
<tr>
<td>1</td>
<td>0.420</td>
<td>0.421</td>
<td>0.100</td>
</tr>
<tr>
<td>Target</td>
<td>0.000</td>
<td>0.003</td>
<td>0.300</td>
</tr>
</tbody>
</table>

Mean Error: 0.350  
Minimum Error: 0.100  
Maximum Error: 0.800

<table>
<thead>
<tr>
<th>Footfalls to the Target (n)</th>
<th>Step Length Measured (m)</th>
<th>Step Length Digitised (m)</th>
<th>Absolute Digitising Error (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1.720</td>
<td>1.718</td>
<td>0.200</td>
</tr>
<tr>
<td>5</td>
<td>1.730</td>
<td>1.725</td>
<td>0.500</td>
</tr>
<tr>
<td>4</td>
<td>1.460</td>
<td>1.459</td>
<td>0.100</td>
</tr>
<tr>
<td>3</td>
<td>1.660</td>
<td>1.656</td>
<td>0.400</td>
</tr>
<tr>
<td>2</td>
<td>1.510</td>
<td>1.515</td>
<td>0.500</td>
</tr>
<tr>
<td>1</td>
<td>1.500</td>
<td>1.502</td>
<td>0.200</td>
</tr>
<tr>
<td>Target</td>
<td>0.420</td>
<td>0.418</td>
<td>0.200</td>
</tr>
</tbody>
</table>

Mean Error: 0.300  
Minimum Error: 0.100  
Maximum Error: 0.500

dimensional motion analysis systems currently available, such as the system by Peak Technologies Inc. Lythgo and Begg’s (1999) data on gait measurements suggests
errors of $\pm 0.5\text{cm}$ for the X-direction (equivalent to toe-to-board distances) and $\pm 0.6\text{cm}$ for step length.
Appendix 6: Anatomical points of the body that were manually digitized in Experiment Four.

The fourteen points that were digitized in Experiment 4 utilising APASWin 2000 software included the ankles (lateral malleolus of fibula), knees (articulation between the lateral condyles of the femur and the tibia), hips (greater trochanter of femur), shoulders (articulation between acromion surface of the scapula and the greater tubercle of the humerus), elbows (articulation between lateral epicondyle of the humerus and head of the radius), wrists (ulna head), vertex between the chin and the neck, and the top of the head, for the right and left sides, as can be seen in Figure A6.1.

Figure A6.1. The fourteen points of the body that were manually digitized for each view of high-speed video footage during the three-dimensional analysis of gymnastic vaulting (adapted from BodyWorks version 5.0).
Appendix 7: The consent forms and plain language statements for Experiments One and Two.

DEAKIN UNIVERSITY ETHICS COMMITTEE
CONSENT FORM:

I, ____________________________

of ____________________________

Hereby consent to be a subject of a human research study to be undertaken by Elizabeth Bradshaw and Tony Sparrow and I understand that the purpose of the research is to investigate the movement patterns of walking, jogging, and sprinting towards different obstacles.

I acknowledge

1. That the aims, methods, and anticipated benefits, and possible risks/hazards of the research study, have been explained to me.

2. That I voluntarily and freely give my consent to my participation in such research study.

3. I understand that aggregated results will be used for research purposes and may be reported in scientific and academic journals.

4. Individual results will not be released to any person except at my request and on my authorisation.

5. That I am free to withdraw my consent at any time during the study, in which event my participation in the research study will immediately cease and any information obtained from me will not be used.

Signature: ____________________________ Date: ____________________________

NOTE: In the event of a minor's consent, or person under legal liability, please complete the Ethics Committee's "Form of Consent on Behalf of a Minor or Dependent Person".
My name is Elizabeth Bradshaw. I am doing a doctoral study in the School of Health Sciences at Deakin University under the supervision of Dr. Tony Sparrow from the School of Health Sciences.

I would like to invite you to participate in a study investigating the movement patterns of walking, jogging and sprinting towards obstacles.

Prior to participation in the study you will be asked to complete a medical questionnaire, which includes questions such as 'Are you a smoker? Has anyone ever told you that you have asthma or a respiratory condition? Have you ever suffered any musculoskeletal injury?'

The study requires participation in four sessions, each of which will be approximately one hour. During the first session a vision test will be administered to check your uncorrected/corrected vision and you will also have your height, eye height, leg length, and shoe length measured. You will then be asked to perform five walking trials at a comfortable pace “as you would around the house”, five jogging trials, and five sprinting trials over a distance of 10m. During the second, third, and fourth sessions you will be asked to repeat the same number of walking, jogging, and sprinting trials, however, you will be asked to negotiate an obstacle. Examples of obstacles which you may be asked to negotiate include a target marked on the floor, a raised surface (box), a hurdle, or a gymnastics take-off board. You may be asked to either step within, onto, or over the obstacle and keep moving, or you may be asked to stop at the obstacle.

During the testing sessions you will be filmed walking, jogging, or sprinting along a marked walkway. The video footage collected will be later captured onto a computer and analysed to determine variables such as your step lengths and velocity. You will be marked with sports-tape to clearly identify the heel, toe, and centre of gravity position. Could you please wear running shoes, bike shorts or leggings, and a crop top or aerobics top (if applicable). This will ensure that the markers can be seen as baggy t-shirts and shorts can hide the markers.

All collected information relating to you will be coded to ensure confidentiality and stored in a locked cabinet for six years, however, you will be given a copy of your results and the overall results and implications upon completion of the study. You may withdraw consent for participation in the project at any time regardless of the reason.

Thank you for taking the time to consider participating in this research project. If you have any questions you can contact Elizabeth Bradshaw, on 9251 7215 or Dr. Tony Sparrow on 9244 6334 at the School of Health Sciences, Deakin University, Burwood.

Should you have any concerns about the conduct of this research project, please contact the Secretary, Ethics Committee, Research Services, Deakin University, 221 Burwood Highway, BURWOOD VIC 3125. Tel (03) 9251 7123 (International +61 3 9251 7123).
Appendix 8: The consent form and plain language statement for Experiment Three

DEAKIN UNIVERSITY ETHICS COMMITTEE

CONSENT FORM:

I,

of

Hereby consent to be a subject of a human research study to be undertaken by Elizabeth Bradshaw and Tony Sparrow and I understand that the purpose of the research is to investigate the movement patterns of sprinting towards targets.

I acknowledge

1. That the aims, methods, and anticipated benefits, and possible risks/hazards of the research study, have been explained to me.

2. That I voluntarily and freely give my consent to my participation in such research study.

3. I understand that aggregated results will be used for research purposes and may be reported in scientific and academic journals.

4. Individual results will not be released to any person except at my request and on my authorisation.

5. That I am free to withdraw my consent at any time during the study, in which event my participation in the research study will immediately cease and any information obtained from me will not be used.

Signature: Date:

NOTE: In the event of a minor's consent, or person under legal liability, please complete the Ethics Committee's "Form of Consent on Behalf of a Minor or Dependent Person".
My name is Elizabeth Bradshaw. I am doing a doctoral study in the School of Health Sciences at Deakin University under the supervision of Dr. Tony Sparrow from the School of Health Sciences.

I would like to invite you to participate in a study investigating the movement patterns of sprinting towards targets.

Prior to participation in the study you will be asked to complete a medical questionnaire, which includes questions such as 'Are you a smoker? Has anyone ever told you that you have asthma or a respiratory condition? Have you ever suffered any musculoskeletal injury?'

The study requires participation in one session of approximately one hour in duration. In the session you will be required to complete a warm-up and cool-down program consisting of 5mins cycling on a stationary bike and stretching. You will also have your height, weight, and shoe length measured. You will then be asked to perform thirty sprinting trials towards a target. You may be asked to either stop within the target or contact the target and keep running (run through). You be will constrained to an error limit of one error per set of five trials. If you make more than one error then you will be asked to complete that set of five trials again.

During the testing sessions you will be filmed sprinting along a marked walkway. The video footage collected will be later captured onto a computer and analysed to determine variables such as your step lengths and velocity. You will be marked with sports-tape to clearly identify the heel, toe, and ankle positions. Could you please wear running shoes, and bike shorts or leggings. This will ensure that the markers can be seen as baggy pants can hide the markers.

All collected information relating to you will be coded to ensure confidentiality and stored in a locked cabinet for six years, however, you will be given a copy of your results and the overall results and implications upon completion of the study. You may withdraw consent for participation in the project at any time regardless of the reason.

Thank you for taking the time to consider participating in this research project. If you have any questions you can contact Elizabeth Bradshaw, on 9251 7215 or Dr. Tony Sparrow on 9244 6334 at the School of Health Sciences, Deakin University, Burwood.
Appendix 9: The consent forms and plain language statements for Experiment Four.

DEAKIN UNIVERSITY ETHICS COMMITTEE

CONSENT FORM:

I, of

Hereby consent to be a subject of a human research study to be undertaken by Elizabeth Bradshaw and Tony Sparrow. I understand that the purpose of the research is to investigate the movement patterns of gymnastic vaulting.

I acknowledge

1. That the aims, methods, and anticipated benefits, and possible risks/hazards of the research study, have been explained to me.

2. That I voluntarily and freely give my consent to my participation in such research study.

3. I understand that aggregated results will be used for research purposes and may be reported in scientific and academic journals.

4. Individual results will not be released to any person except at my request and on my authorisation.

5. That I am free to withdraw my consent at any time during the study, in which event my participation in the research study will immediately cease and any information obtained from me will not be used.

Signature: Date:

NOTE: In the event of a minor's consent, or person under legal liability, please complete the Ethics Committee's "Form of Consent on Behalf of a Minor or Dependent Person".
DEAKIN UNIVERSITY ETHICS COMMITTEE
CONSENT ON BEHALF OF A MINOR OR DEPENDENT PERSON

I,                                            of

Hereby give consent for my son / daughter / dependent

to be a subject of a human research study to be undertaken by Elizabeth Bradshaw and Tony Sparrow.

I understand that the purpose of the research is to investigate the movement patterns of gymnastic vaulting.

I acknowledge that

1. The aims, methods, and anticipated benefits, and possible hazards/risks of the research study, have been explained to me.

2. I voluntarily and freely give my consent to my child's / dependent's participation in such research study.

3. I understand that aggregated results will be used for research purposes and may be reported in scientific and academic journals.

4. Individual results will not be released to any person including medical partitioners.

5. I am free to withdraw my consent at any time, during the study in which event my child's/dependent's participation in the research study will immediately cease and any information obtained will not be used.

Signature:                                      Date:

NOTE: The parent or parents, or person(s) having guardianship of the child must sign the consent form.
DEAKIN UNIVERSITY ETHICS COMMITTEE
CONSENT FORM – For Institutions/Organisations

I, ................................................................. of .................................................................
.................................................................................................................................

Hereby give permission for .................................................................

to be involved in a research study being undertaken by Elizabeth Bradshaw and Tony Sparrow.

I understand that the purpose of the research is to investigate the movement patterns

gymnastics vaulting,

and that involvement for the institution means the following:-

I acknowledge that

1. The aims, methods, and anticipated benefits, and possible risks/hazards of the research
study, have been explained to me.

2. I voluntarily and freely give my consent for the institution/organisation to participate in
the above research study.

3. I am free to withdraw my consent at any time during the study, in which event
participation in the research study will immediately cease and any information obtained
through this institution/organisation will not be used if I so request.

4. I understand that aggregated results will be used for research purposes and may be
reported in scientific and academic journals.

I agree that

4. The institution/organisation MAY / MAY NOT be named in research publications or other
publicity without prior agreement.

5. I / We DO / DO NOT require an opportunity to check the factual accuracy of the research
findings related to the institution/organisation.

6. I / We EXPECT / DO NOT EXPECT to receive a copy of the research findings or publications.

Signature: ................................................................. Date: ______________________
My name is Elizabeth Bradshaw. I am doing a doctoral study in the School of Health Sciences at Deakin University under the supervision of Dr. Tony Sparrow from the School of Health Sciences.

I would like to invite you to participate in a study investigating the movement patterns of gymnastics vaulting.

The study requires participation in a vaulting session of approximately one and a half hours in duration. At the beginning of the experiment, after your regular warm-up and conditioning, you will have your height and weight measured. You will then be asked to perform five sprinting trials towards a take-off board, completing a round-off onto the board and a backward double salto onto a landing mat. The running distance for this task will be the same distance that you run when vaulting. You will then be asked to complete your normal vaulting warm-up for a yurchenko entry vault, prior to completing five vaulting trials. Your coach will be present at all times.

During the testing sessions you will be filmed sprinting along the vaulting strip and when performing your vaults. A judge will also be present to score your performance during the vaulting section of the experiment. All video footage collected will be later captured onto a computer and analysed to determine variables such as your step lengths and velocity, as well as your peak height and time in the air during the post-flight phase of your vaults. Could you please wear a training leotard without bike pants.

All collected information relating to you will be coded to ensure confidentiality and stored in a locked cabinet for six years, however, you will be given a copy of your results and the overall results and implications upon completion of the study. You may withdraw consent for participation in the project at any time regardless of the reason.

Thank you for taking the time to consider participating in this research project. If you have any questions you can contact Elizabeth Bradshaw, on 9251 7215 or Dr. Tony Sparrow on 9244 6334 at the School of Health Sciences, Deakin University, Burwood.
Dear Parent/Guardian,

My name is Elizabeth Bradshaw. I am doing a doctoral study in the School of Health Sciences at Deakin University under the supervision of Dr. Tony Sparrow from the School of Health Sciences.

I would like to invite your daughter to participate in a study investigating the movement patterns of gymnastics vaulting.

The study requires your daughter to participate in a vaulting session of approximately one and a half hours in duration. After your daughter has completed her regular warm-up and conditioning, she will have her height and weight measured. Your daughter will then be asked to perform five sprinting trials towards a take-off board, completing a round-off onto the board and a backward double salto onto a landing mat. The running distance for this task will be the same distance that your daughter runs when vaulting. Your daughter will then be asked to complete her normal vaulting warm-up for a yurchenko entry vault, prior to completing five vaulting trials. Your daughter’s coach will be present at all times.

During the testing sessions your daughter will be filmed sprinting along the vaulting strip and also when performing her vaults. A judge will also be present to score your daughters performance during the vaulting section of the experiment. The video footage collected will be later captured onto a computer and analysed to determine variables such as step lengths and velocity, as well time in the air and peak height during the flight phase of her vaults.

All collected information relating to your daughter will be coded to ensure confidentiality and stored in a locked cabinet for six years, however, your will be given a copy of her individual results and the overall results and implications upon completion of the study. You may withdraw consent for your daughter’s participation in the project at any time regardless of the reason.

Thank you for taking the time to consider the participation of your daughter in this research project. If you have any questions you can contact Elizabeth Bradshaw, on 9251 7215 or Dr. Tony Sparrow on 9244 6334 at the School of Health Sciences, Deakin University, Burwood.

Should you have any concerns about the conduct of this research project, please contact the Secretary, Ethics Committee, Research Services, Deakin University, 221 Burwood Highway, BURWOOD VIC 3125. Tel (03) 9251 7123 (International +61 3 9251 7123).
My name is Elizabeth Bradshaw. I am doing a doctoral study in the School of
Health Sciences at Deakin University under the supervision of Dr. Tony Sparrow
from the School of Health Sciences.

I would like to invite your gymnasts to participate in a study investigating the
movement patterns of gymnastics vaulting.

The study requires six gymnasts to participate in a vaulting session of
approximately one and a half hours duration. The study will involve the gymnasts
completing their regular warm-up and then having their height and weight measured,
followed by two tasks. The first task involves five sprinting trials towards a take-off
board, completing a round-off onto the board and a backward double salto onto a
landing mat. The running distance for this task will be the same distance that the
gymnasts run when vaulting, and the purpose of the double salto is to try and maintain
a similar level of difficulty between the two tasks being measured experimentally. The
second task involves five yurchenko vaulting trials, after the regular warm-up for
vaulting. It is preferable that the gymnasts complete vaults during this section of the
experiment, which have a start value of 9.2 or greater to ensure that the difficulty of
the task is the same as encountered when competing.

During the testing sessions the gymnasts will be filmed using one panning
camera sprinting along the vaulting strip. In addition to this, during the vaulting
section of the experiment two stationary cameras will film the gymnasts vaults three-
dimensionally and a judge will be employed to score the performance of the vaults.
The approach strip will be marked with white gaffa tape on the outer edges every
0.50m to provide a scale for the film obtained. The video footage collected will be
later captured onto a computer and analysed to determine variables such as the
gymnasts step lengths and velocity, and time in the air and peak height of the flight
phase of the vaults. The gymnasts will be asked to wear a training leotard without
bike pants.

All collected information relating to the gymnasts will be coded to ensure
confidentiality and stored in a locked cabinet for six years, however, you will be given
a copy of the overall results and implications upon completion of the study. You may
withdraw consent for your gymnasts’ participation in the project at any time
regardless of the reason. During the experiment your gymnasts’ safety will be the first
priority. If you have any concerns at any time during the testing session you can either
ask for modification to the testing set-up, such as adding extra matting or spotting the
gymnast, or you can withdraw the gymnast or gymnasts from the study.
Thank you for taking the time to consider the participation of your gymnasts' in this research project. If you have any questions you can contact Elizabeth Bradshaw, on 9251 7215 or Dr. Tony Sparrow on 9244 6334 at the School of Health Sciences, Deakin University, Burwood.

Should you have any concerns about the conduct of this research project, please contact the Secretary, Ethics Committee, Research Services, Deakin University, 221 Burwood Highway,
Appendix 10: The medical questionnaire for Experiments One, Two and Three.

DEAKIN UNIVERSITY ETHICS COMMITTEE
MEDICAL QUESTIONNAIRE

NAME: ....................................  AGE: ....... (yrs)  SEX: .......
BODY MASS: ............ (kg)  HEIGHT: .......... (cm)

Are you currently undertaking any form of regular exercise?  YES  NO
If yes, briefly describe the type and amount (i.e. frequency, duration) of exercise you perform.

Are you a smoker?  YES  NO
Has anyone ever told you that you:
- are overweight?  YES  NO  UNKNOWN
- have high blood pressure?  YES  NO  UNKNOWN
- have a heart condition or heart murmur?  YES  NO  UNKNOWN
- have asthma or a respiratory condition?  YES  NO  UNKNOWN
- have diabetes?  YES  NO  UNKNOWN
- have a bleeding disorder (e.g. haemophilia)?  YES  NO  UNKNOWN

Have you ever had:
- chest pain, chest discomfort, chest tightness or chest heaviness?  YES  NO  UNKNOWN
- shortness of breath out of proportion to exercise undertaken?  YES  NO  UNKNOWN
- heart palpitations (sensation of abnormally fast and/or irregular heart beat)?  YES  NO  UNKNOWN
- episodes of fainting, collapse or loss of consciousness?  YES  NO  UNKNOWN
- abnormal bleeding or bruising?  YES  NO  UNKNOWN

Do you have a family history of cardiovascular disease? (e.g. heart attack, chest pain/angina, stroke, rheumatic heart disease)  YES  NO  UNKNOWN
If YES, please elaborate:
Have you ever suffered any musculoskeletal injury?  
If YES, please elaborate:  
YES NO UNKNOWN

Do you have any allergies? (including to medications)  
If YES, please elaborate:  
YES NO UNKNOWN

Are you currently on any medication?  
If YES, please describe:  
YES NO

Are you currently taking anabolic steroids or any other performance-enhancing agents?  
YES NO

Neither the investigators nor Deakin University condone the use of anabolic steroids or other banned substances known to enhance athletic performance; however, in certain circumstances, information on their use is required for research purposes.

Is there any other reason which you know of that would prevent you from undertaking the proposed exercise and other tests?  
If YES, please elaborate:  
YES NO

I believe the information I have provided to be true and correct.

SIGNED: .............................................  DATE: ......................

COMMENTS ON MEDICAL EXAMINATION (where appropriate):
Appendix 11: The age and anthropometric characteristics of the participants in Experiment One.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Age (year)</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>Shoe Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1F1</td>
<td>25</td>
<td>1.63</td>
<td>65.00</td>
<td>0.28</td>
</tr>
<tr>
<td>1F2</td>
<td>23</td>
<td>1.69</td>
<td>60.00</td>
<td>0.26</td>
</tr>
<tr>
<td>1F3</td>
<td>23</td>
<td>1.80</td>
<td>68.00</td>
<td>0.28</td>
</tr>
<tr>
<td>1F4</td>
<td>22</td>
<td>1.64</td>
<td>54.00</td>
<td>0.27</td>
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</tr>
<tr>
<td>1F6</td>
<td>21</td>
<td>1.70</td>
<td>57.00</td>
<td>0.28</td>
</tr>
<tr>
<td>1M1</td>
<td>24</td>
<td>1.83</td>
<td>70.00</td>
<td>0.32</td>
</tr>
<tr>
<td>1M2</td>
<td>23</td>
<td>1.91</td>
<td>90.50</td>
<td>0.31</td>
</tr>
<tr>
<td>1M3</td>
<td>22</td>
<td>1.70</td>
<td>73.40</td>
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</tr>
<tr>
<td>1M4</td>
<td>26</td>
<td>1.81</td>
<td>88.40</td>
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</tr>
<tr>
<td>1M5</td>
<td>27</td>
<td>1.80</td>
<td>78.00</td>
<td>0.30</td>
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<td>1M6</td>
<td>27</td>
<td>1.81</td>
<td>90.00</td>
<td>0.31</td>
</tr>
<tr>
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<td><strong>1.69</strong></td>
<td><strong>59.00</strong></td>
<td><strong>0.28</strong></td>
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<tr>
<td><strong>Male</strong></td>
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<td><strong>1.81</strong></td>
<td><strong>81.72</strong></td>
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<td><strong>Mean</strong></td>
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<td><strong>1.75</strong></td>
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Appendix 12: The age and anthropometric characteristics of the participants in Experiment Two.

<table>
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<tr>
<th>Participant</th>
<th>Age (year)</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>Leg Length (m)</th>
<th>Shoe Length (m)</th>
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<tbody>
<tr>
<td>2F1</td>
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<td>0.26</td>
</tr>
<tr>
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<td>0.27</td>
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<td>0.30</td>
</tr>
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<td>90.45</td>
<td>1.00</td>
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<td>0.95</td>
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<th>Gender</th>
<th>Age Mean</th>
<th>Height Mean</th>
<th>Weight Mean</th>
<th>Leg Length Mean</th>
<th>Shoe Length Mean</th>
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<tbody>
<tr>
<td>Female</td>
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<td>1.63</td>
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Appendix 13: The age and anthropometric characteristics of the participants in Experiment Three.

<table>
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<th>Age (years)</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>Shoe Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>3F2</td>
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<td>1.67</td>
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<td>0.28</td>
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<td>3M1</td>
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<td>81.00</td>
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<td>69.00</td>
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<td>69.00</td>
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</tr>
<tr>
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<td>1.69</td>
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</tr>
<tr>
<td>Male</td>
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<td>1.79</td>
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<td>0.29</td>
</tr>
<tr>
<td>Mean</td>
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Appendix 14: The age and anthropometric characteristics of the participants in Experiment Four.

<table>
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<th>Height (m)</th>
<th>Weight (kg)</th>
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<tbody>
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<td>46.9</td>
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</tbody>
</table>