DEVELOPMENTAL TRENDS IN SKILLED LOCOMOTOR BEHAVIOR OVER UNEVEN TERRAIN

by

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Abstract

The primary focus of this thesis was to examine the development of obstacle avoidance strategies in children. In particular, the role played by vision in modulating the locomotor pattern over obstacles was investigated. A theoretical model was proposed and its components were addressed. In order to pursue this goal, three studies were planned and conducted.

The goal of the first study was to characterise the contribution of visual exteroceptive input to obstacle avoidance strategies. Exteroceptive information refers to identification of location and features of objects and surfaces in the environment. For a child, the perception of exteroceptive information and the appropriate motor pattern modulation of the intended action are processes that are developed through sensory-motor integration. Exteroceptive information was manipulated through a combination of two obstacle heights and two obstacle widths, all with high contrast between the obstacle and the ground. Subjects (n=25, 2 to 58 months of walking experience) were asked to step over an obstacle placed in their travel path. Video recording with a split screen two-camera system was done to qualitatively document each child's performance. Seven IREDs were placed on specific anatomical landmarks (right and left hip and toe, right knee, ankle and heel) and sampled using the OPTOTRAK motion analysis system (Northern Digital, Canada). From the displacement of the markers from leading toe off to trailing foot contact, four dependent measures were obtained: leading and trailing toe clearance, leading hip elevation and leading foot placement before the obstacle. Results from the qualitative measures did not reveal developmental trends, indicating that children were able to perform the task but they need to tune their limb trajectories to safely clear the obstacle. The kinematic measures confirmed the qualitative results indicating that obstacle height influenced the modulation of the limb displacements over the obstacle.

The second study examined the role of expproprioceptive information in modulating the locomotor pattern over obstacles. Exproprioceptive information refers to the identification of the body parts relative to one another and relative to the objects and events in the environment. Expproprioceptive information was manipulated through a combination of two obstacle heights with low contrast and by either restricting or not vision from both limbs. Subjects (n=20, from 8 to 62 months of walking experience) were asked to wear a neck collar and step over an obstacle placed in their travel path. Qualitative video analysis was performed as in the first study. Kinematic analysis was done on the displacement of five IREDs (right and left eye, shin and right and left toe) to obtain gait and head parameters. The results from the qualitative measures (failure rate) exhibit a developmental trend, indicating that a more challenging environment was necessary to exhibit this trend. Gait kinematic measures (leading and trailing toe clearance and foot placement before the obstacle) replicated the results of the first study. Head kinematic measure (pitch angle magnitude) revealed a developmental trend in spatio-temporal acquisition of exteroceptive and expproprioceptive information, especially when vision was restricted.

The third study focused on the contribution of the effector system's intersegmental dynamics during locomotion over obstacles through a kinetic analyses of the swing limb. Kinetic analysis offers a special opportunity to verify the exploitation of the passive and active forces acting on the limb during the swing phase. Successful trials from the first study were reanalysed through the inverse dynamics technique, which allows the isolation of the muscle moment from motion dependent moments and gravity. The muscle moments around the hip and the ankle joints were modulated as a function of obstacle height. This modulation revealed that the nervous system was actively controlling the swing limb flexion over the obstacle, even though it is not efficient.

The results of the three studies support the proposed theoretical model.

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Please forgive me if I forgot someone.

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To my parents and grandparents, by their encouragement and emotional support, I just hope to be to my sons and grandchildren what you have been to me.

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Dedication

I would like to dedicate this thesis to my family: my sons Ronaldo and Peri, and my husband Sebastiao. Your love is my energy and determination.

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Introduction

Independent walking is a critical milestone in a child's development. The development of over ground independent bipedal locomotion in children has been extensively studied since the early 1930s (Shirley, 1931; McGraw, 1932; McGraw, 1940; Bernstein, 1940; Zelazo, 1983; Wickstrom, 1983; Sutherland, et al., 1988). Kinematic, kinetic, and muscle activation patterns during locomotion over level ground have been well documented (Shirley, 1931; Sutherland, et al., 1988; Wickstrom, 1983; Zelazo, 1983; Bril et al., 1993; Forssberg, 1985; Bronstein et al., 1996). Since a child: a) must interact in an adult-oriented environment (i.e., house furniture, stairs, curbs), b) has immature and non- integrated perceptual and motor systems, and c) demonstrates insufficient posture and balance control, it is essential to understand the relationship between the structures and processes that modulate a robust system so an individual can successfully act in the environment.

Parents attempt to decrease the demands of their child's environment by clearing obstacles from the travel path during the transition from supported walking to the onset of independent locomotion. Following the emergence of independent locomotion, children begin to interact within a challenging and complex environment. However, as Shumway-Cook and Woollacott (1995) pointed out, the study of the developmental adaptations of walking over obstacles has not been adequately addressed. Rosengren and Wells (1994) qualitatively described walking over obstacles (2, 4, 8, and 16 cm) in three- and four-year-old children. Gait adjustments were observed prior to (i.e., shorter strides and reduced velocity of locomotion), over (i.e., raising the arms, leaning forward), and after (such as toe landing first) the obstacle and were dependent on obstacle height. Patla, Prentice and Gobbi (1996) reported preliminary results on obstacle avoidance strategies in children. High failure rate and poor control of limb trajectory characterised the gait patterns of children as they stepped over obstacles.

Toys located on the ground are common obstacles encountered by a child. To avoid the toy or obstacle, the child must identify the obstacle in his/her environment and use the sensory information received to select an appropriate obstacle avoidance strategy. The selected strategy could involve sensori-motor transformation so that the lower limbs successfully clear the obstacle. Alternatively, the child may choose to avoid the obstacle by simply travelling around it. Successful obstacle avoidance requires the integration of visual and kinesthetic sensory input with the dynamics of the effector system, which include muscle strength and joint range of motion. The major goal of the thesis was to study the characteristics of obstacle avoidance strategies in children following the emergence of independent bipedal locomotion and thus document sensori-motor transformation development in children. The following sections address the perception and action components that are crucial for obstacle avoidance.

Sensory Information (Perception)

According to the followers of the Perception-Action Theory (Gibson, 1979; Gibson, 1982; Adolph et al., 1993), the concept of affordances represents the link between external information and the performed action. Affordances are invariant combinations of properties of the objects and events of the environment taken with reference to the animal (Gibson, 1979; Gibson, 1982). Light reflected from textured surfaces and objects that rest on the surfaces form an ambient array available to an observer. The ambient array is detected by the retina. For an adult observer, the detection of the ambient array occurs directly and controls action. However, for a child that has just recently developed independent locomotion and has an immature visual apparatus, the perception of the invariant properties of the environment and the appropriate motor pattern modulation of the intended action are processes that develop through sensori-motor integration. Infants can detect object properties through exploration and learn how to modify their actions accordingly (Adolph et al., 1993). Thus, "the human young must learn to perceive affordances" ((Gibson, 1982) p. 406). Then, when a child has to make a decision for one among the obstacle avoidance strategies to safely walk in a cluttered environment, his/her decision may also depend on body scale. Body scale refers to the internal representations of the external objects and events according to the subject's body features. A child explores the environment, builds his/her affordances and continually updates them according to his/her asymmetric physical growth in order to keep affordances adjusted to body scale. The anthropometric characteristics of a child are intrinsic in his/her affordances. Body scale, as well as perception, also implies control of action. Affordances are directly detected and guide actions. Thus, obstacle height and width should be based on the anthropometric characteristics of the children in accordance with the affordance principle.

In order to perceive affordances and to clear an obstacle in an efficient and safe manner, sensory information from the visual system must be used. Visual input is especially crucial in order to finely modulate the locomotor pattern to adjust to the demands of the environment. Let us review some important aspects of the visual system and how it develops.

Chandna (1991) has discussed the rapid progress of visual function from relative immaturity within the first 6 to 8 months of life to reaching adult levels by the age of five. Hood (1988) emphasized that developmental changes in visual perception during the first year of life involve major retinal changes. Rods and cones, the light-sensitive cells of the human eye, are located in the retina. In the adult's retina, rods are responsible for gross, black-and-white vision while cones respond to fine lines and colour. Cones are concentrated in the fovea, a 0.7 mm spot located in the center of the retina. Foveal vision permits us to see most of the environment. In a newborn's retina, rods are quite mature but the same cannot be said about the cones. The immature fovea of the newborn allows for only a poor sensitivity to contrast (Banks et al., 1988). The fovea is not fully formed at birth because cones are both distributed in a larger area and are not elongated yet. The central migration of the cones, which permits a progressive increase of population density, occurs over a time course of three years (Chandna, 1991). To activate the cones, a newborn requires more light than an adult. So in order for a newborn to distinguish between two levels of light, the difference between the two light levels must be greater than for an adult. Compared with that of adults, the visual acuity in neonates is also limited. The newborn's perception of the environment may be similar to that of subjects with age-related maculopathy (i.e., degeneration of the fovea). However, at the end of the first year, infants show a huge improvement in their abilities to see lines (Banks et al., 1988) and they achieve adult levels of spatial resolution and contrast sensitivity during the first five years of human life (Movshon et al., 1988).

Foveal immaturity is not solely responsible for poor visual acuity in newborns. Stanley (1991) has pointed out that the increasing functional independence of the columnar units in the striate cortex also improves visual perception. This columnar independence is achieved by the linkage of cells extending from the cortical surface to the subcortical white matter in a mature cortex. However, Stanley (1991) has discussed the necessity of electrophysiological and psychophysical studies in fetuses and infants to elucidate the relationship between the developing columns and the mature hypercolumns. The mature hypercolumns in the striate cortex allow for an accurate visual perception of the environment.

Visual acuity, the spatial properties of visual performance, involves contrast sensitivity, the ability to discriminate different levels within the same colour target; both are treated interchangeably in the literature (Morrone et al., 1993; Movshon et al., 1988). Adoh and Woodhouse (1994) applied the Cardiff Acuity Test (CAT) to estimate visual acuity in 231 toddlers ranging in age from 12 to 36 months. They found good success rates, as determined by the ratio between the tested children and the total number of children brought into the test setting, in this age group (96% at 12 months and 100% at 36 months) with test-time decreasing from 3.42 minutes at 12 months to 2.26 minutes at 36 months. Their results also showed a linear improvement in visual acuity according to age: at 12 months the mean binocular acuity was 4.5 minutes of arc while at 36 months it was 1.2 minutes of arc. It is also important to note that during the first year, the infants had opportunities to experience some rudimentary forms of locomotion such as crawling and supported walking. The temporal coincidence of the maturation of the fovea and the emergence of independent locomotion may affect obstacle avoidance strategies.

The visual system extracts two types of information required to promote a safe and low energy cost locomotion over obstacles: exteroceptive and exproprioceptive information. Exteroceptive information refers to the identification of locations and features of objects and surfaces in the environment (Gibson, 1979; Gibson, 1982). Human individuals mainly extract exteroceptive information through the use of vision; however, infants and blind people can extract exteroceptive information through haptic and auditory inputs. During locomotion over uneven terrain, exteroceptive input is necessary to plan in advance adaptive strategies. Information received about the obstacle characteristics (i.e., dimensions, and location of the obstacle) and the terrain properties allows us to adapt accordingly. Sensori-motor transformation integrates the sensory information received in order to modulate the effector system to produce adaptive locomotor patterns. Past research in young and older adults which manipulated exteroceptive information by altering obstacle and terrain properties (Patla et al., 1996; Patla et al., 1995b; Patla et al., 1993a; Patla et al., 1993b) are described below.

Research investigating the manipulation of exteroceptive information and its effects on obstacle avoidance strategies in children has been limited. Rosengren and Wells (1994) qualitatively described walking over obstacles (2, 4, 8 and 16 cm high) in three- and four-year-old children. They observed gait adjustments, related to obstacle height, prior to, over, and after the obstacle. As the obstacle height increased, children performed more anticipatory adjustments, such as decreasing both the stride length and the velocity of locomotion. Postural adjustments such as leaning forward and raising the arms were observed when the children stepped over the obstacle. After the obstacle, younger children especially landed on the toes of the foot. Interestingly, all the changes observed when stepping over obstacles are also observed early in the development of the walking pattern. These behavioural changes may indicate a regression in motor pattern, which occurs when challenging situations are encountered by a child. Patla et al. (1996) assessed the kinematics of obstacle avoidance strategies as children stepped over obstacles of different heights (0.5, 6 and 14 cm). Children ranged in age from 14 to 30 months. The subjects showed a large safety margin as revealed by higher toe clearance values for all obstacle heights. They had similar toe clearance values for the leading and trailing limbs, except when stepping over the highest obstacle. Qualitatively, subjects experienced great difficulty with the smallest obstacle (0.5 cm height), either hitting, stepping on, or touching the obstacle more often with the leading and/or trailing limb. The relative contribution of hip hiking to toe clearance was higher for young children (over 30%) as compared to young adults (around 20%). Interestingly, the values for young children were similar to older adults. Based on relatively small changes documented in the angular displacements of the hip, knee and ankle joint, it was speculated that the larger contribution of hip hiking to toe clearance may reflect an inability to exploit the passive intersegmental dynamics of the system to achieve swing limb flexion over obstacles. Another critical kinematic measure was the leading limb foot placement at toe-off before the obstacle. Young children displayed higher variability on this parameter indicating poor stride adjustments prior to going over the obstacle. For example, the values for one subject ranged from 14% (i.e., foot placed close to obstacle) to 65%, a value which is closer to that observed for young adults. Patla et al. (1996) proposed that the ingredients of the skilled locomotor pattern over obstacles are not yet sculpted or integrated in children as indicated by the poor avoidance strategies observed.

Ascent and descent locomotion on ramps with different slopes (i.e., alteration of terrain properties) was studied in 14-month-old children (Adolph, 1995). The major purpose of this study was to assess psychophysically the child's perceptual judgement accuracy and his/her motor skills to go up and down slopes. The results showed that, on average, perceptual judgements were scaled to locomotion skills on slopes. Visual and tactile perceptual judgements were related to the slope angles, that is, infants crawled instead of walked on the steeper slopes. The choice to crawl instead of walk at the steeper slopes revealed a regression of the locomotor pattern, as observed by Rosengren and Wells (1994). The children with more walking experience perceived the environment better and explored the environment more efficiently by hesitating, touching or testing the slope before making the decision about which locomotor pattern to use for the task. It has been suggested that tactually or visually exploring the locomotion terrain is a more prudent form of exploratory activity (Gibson et al., 1987).

The second type of visual information utilized in obstacle avoidance is exproprioceptive information. Exproprioceptive information refers to the identification of the body parts relative to one another and relative to the objects and events in the environment and is provided by vision (Gibson, 1979; Gibson, 1982; Lee et al., 1986). Exproprioceptive inputs provide information about the orientation of limbs and their positions and velocities as they go over obstacles. Thus, exproprioceptive information plays a role in the control of limb elevation (Patla et al., 1995b) and is necessary for walking over obstacles because subjects must tune their body segment's motion to ensure safe clearance. The leading limb and the obstacle can be seen when stepping over the obstacle but the trailing limb and the obstacle are not viewed when crossing over the obstacle. Through a comparison of the leading versus trailing limb trajectories, it is possible to investigate the role of exproprioceptive cues in the control of locomotion. Another way to examine the contribution of exproprioceptive information during walking over obstacles is to restrict the view of both limbs. This restriction can be accomplished by asking subjects to wear goggles (Patla et al., 1993b; Patla et al., 1995b), or a collar or to hold an object in front of their body. Under visual restrictions, subjects may plan adaptive strategies several steps prior to the obstacle and/or monitor the leading limb over the obstacle through forward flexion of the neck.

Patla et al. (1993b) conducted a study manipulating expropriοceptive input during obstacle avoidance in young adults. Two obstacle heights (6 and 26 cm) plus a "no-obstacle" condition and the presence and absence of expropriοceptive input (goggles vs. no goggles) were combined. The major finding was related to compensation by the kinematic parameters of gait when expropriοceptive information was absent. Specifically, subjects showed an increased toe clearance and an anterior foot placement at toe-off before the obstacle both for the leading and trailing limbs when vision was restricted. A second study by Patla et al. (1995b) analysed how expropriοceptive information affects the kinematic parameters of the locomotion over solid and fragile obstacles in young adults by comparing the leading limb versus the trailing limb. An increase in trailing limb toe clearance was expected; however the subjects revealed similar lead and trail toe clearance results within the same obstacle feature. The lack of visual expropriοceptive input resulted in higher variability in elevation of the trailing toe over obstacles. These results indicated that visual information from the leading limb stepping over obstacles facilitates the trajectory of the trailing limb.

Another type of information also necessary for locomotion is kinesthetic information. Kinesthetic input provides information about stance and swing limb position and velocity and body orientation referenced to the ground. Muscles and joint receptors are responsible for providing kinesthetic input, which assists limb elevation over obstacles. The knowledge of the toe location is necessary in order to provide an adequate safety margin over the obstacle. Intersensory coupling between the visual and kinesthetic systems and sensorimotor coupling or transformation are necessary for safe and efficient obstacle avoidance. The ability to combine sensory information and act on it accordingly allow individuals to effectively adapt their obstacle avoidance strategies to a changing environment, a skill not yet achieved by a child in the stages of development. Now, let us review some important aspects of the effector system.

Effector System (Action)

A child's effector system, which includes the bones, muscles, peripheral nervous system and the soft tissues, undergoes extensive changes during infancy and childhood. These changes are not only morphological but also functional, such as muscle force, range of motion and the relationship among the component parts of the effector system. The utilisation of the effector system dynamics in the expression of posture and locomotion has been shown (Shumway-Cook et al., 1995; Schneider et al., 1990; Jensen et al., 1994;

Ulrich et al., 1994). Let us focus now on some aspects of the development of posture and their implication for locomotion related to the effector system.

Shumway-Cook and Woollacott (1995) presented an elegant literature review about the theories of postural control development. The development of postural control occurs continually as the different sensory and motor systems develop, but the behavioural manifestation is discontinuous with some regression observed as the children include new strategies in their repertoire. Acquisition of independent locomotion forces children to control dynamic equilibrium against gravity. Even though it has been said that young children are "fearless" because they are closer to the ground, head size and weight bring up their centre of mass to the T12 level in comparison to L5-S1 in adults (Shumway-Cook et al., 1995). The location of the center of mass, the smaller base of support (when compared with lying and sitting), and total body height produce faster body sway than adults in standing (Shumway-Cook et al., 1995; Bronstein et al., 1996). However, it is interesting that children 4 to 6 years-old showed slower and more variable postural responses to applied perturbations than 15-month- to 3 year-old and 7- to- 10 years of age. The electromyographic (EMG) results also suggested a regression in the postural response organisation (Shumway-Cook et al., 1995). Exproprioceptive and exteroceptive input are also necessary for the dynamic control of posture; an important consideration when stepping over obstacles. When children then have to deal with a complex environment such as obstacles in their travel path, balance control can not be compromised and must be considered in the selection of the proper avoidance strategies.

Effector system properties include muscle strength and joint range of motion, and intersegmental dynamics refer to the passive forces and moments acting on the multi-linked skeletal system. Effector system modulation includes the exploitation of the passive forces acting on the limb. According to Smith et al. (1991), the central nervous system (CNS) deals separately with movement dynamics (forces and torques) and kinematics (direction, velocity, acceleration). *Inverse Dynamics Analysis* (ID) attempts to explain how the CNS controls limb movements based on the generation of joint torques. The analysis takes into account not only muscle activity but also gravity and passive reaction forces coming from the actions that contribute to the subsequent movement. In order to generate smooth and efficient movements, the CNS must manage the mechanically linked segmental masses moving through a three-dimensional gravitational field (Bernstein, 1967). Bernstein (1940) emphasized what he called *"different effects of the same initial innervation"*. That is, there is not a one-to-one correspondence between force (of the muscles) and movements (of the limb) because the initial conditions (position, velocity and force field) may change from time to time. The CNS actively controls only the muscle forces (Schneider et al., 1990), whereas the passive mechanical properties are exploited to drive and enhance skilled movements (Bernstein, 1967).

The inverse dynamic analysis is a technique that can identify and quantify both the underlying forces and joint patterns acting on limbs and their changes with context and experience (Schneider et al., 1990). The method of inverse dynamics is useful in order to yield the active and passive components acting on limb joints during unrestrained motion. The requirements to correctly perform the inverse dynamics calculations are accurate measurements of segment masses, centres of mass, joint centres, and moments of inertia (Winter, 1990). Intersegmental dynamics use a mathematical model of the human body based on anthropometric measures (Schneider et al., 1990). The forces acting to produce movement are muscle forces, gravitational forces, and the motion dependent term (Winter, 1990). For a more specific literature review about the effector system refer to the Introduction section of Study # 3. Based on the literature presented above and on an extensive research data base investigating obstacle avoidance strategies in young and elderly adults, Patla et al. (1996) proposed the theoretical model presented next.

Theoretical Model

Patla, Prentice and Gobbi (1996) proposed a theoretical model or jigsaw puzzle metaphor to summarize the salient features of obstacle avoidance strategies. The jigsaw puzzle metaphor is illustrated in Figure 1. The metaphor is based on extensive research, in young adults and elderly, investigating the parameters affecting obstacle avoidance strategies, particularly vision, conducted by Patla and collaborators during the past decade (Patla et al., 1989; Patla et al., 1992a; Patla et al., 1993a; Patla et al., 1993b; Patla et al., 1994; Patla et al., 1995b). In the model, key components for successful, efficient obstacle avoidance are summarized as pieces of a jigsaw puzzle. The components are visual exteroceptive input, visual exproprioceptive input, kinesthetic input, effector system properties, and intersegmental dynamics. The jigsaw puzzle metaphor reveals the relationship within and between each key component and the changes that occur during normal development and aging.

The authors argue that the components of obstacle avoidance strategies are present in children but are neither sculpted nor integrated. During the development of obstacle avoidance strategies, the individual pieces of the puzzle are sculpted and integrated to generate successful and efficient strategies as revealed in the puzzle representing the young adult. It is assumed that development represents a combination of both maturation and learning processes supporting Karmiloff-Smith's (1992) approach that is time to understand development as an integration of some built-in knowledge and experience. During the normal aging process, cracks appear in the puzzle and thus the relation between the component parts of the puzzle deteriorates and adaptive obstacle avoidance strategies may be implemented. Patla et al. (1996) assume that balance is achieved through the sculpting and integration of the components in the puzzle.

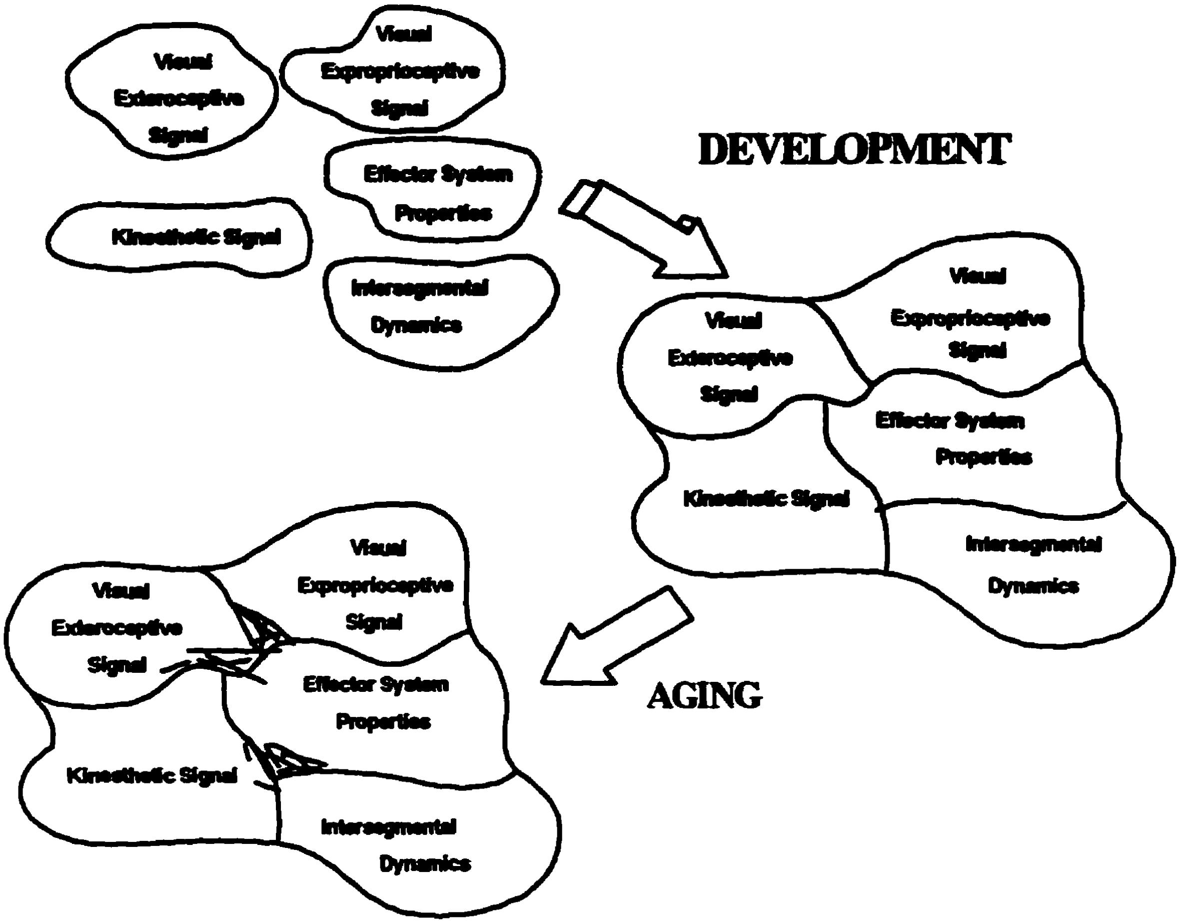

Figure 1. Key ingredients for successful, efficient obstacle avoidance strategy are summarized as pieces of a jigsaw puzzle. During development of this strategy, the pieces of the puzzle are sculpted and brought together. Under normal aging process chunks (shown as shaded areas in the pieces) appear in the puzzle. Visual exteroceptive input includes information about obstacle and terrain properties; visual exproprioceptive input provides information about body and limb orientation and velocity; kinesthetic input includes stance and swing limb position and velocity and body orientation referenced to ground; effector system properties include muscle strength and joint range of motion; and intersegmental dynamics refer to, among other things, the passive forces and moments acting on the multi-linked skeletal system.

Rationale

The primary focus of this thesis was to examine the development of obstacle avoidance strategies in children. In particular, the role played by vision in modulating the locomotor pattern over obstacles was investigated. In order to pursue this goal, three studies were planned and conducted. The goal of the first study was to characterise the contribution of visual exteroceptive input to obstacle avoidance strategies. The development of obstacle avoidance strategies was studied by having children step over obstacles of different height and width. The second study examined the role of exproprioceptive information in modulating the locomotor pattern over obstacles. Children stepped over obstacles of different height with normal vision or with vision of the limbs restricted. The third study focused on the contribution of the effector system during locomotion over obstacles using intersegmental dynamic analyses of the swing limb. Exteroceptive input, exproprioceptive information and intersegmental dynamics are three key ingredients of the puzzle (Refer to Figure 1). The decision to focus on these three components was based on the assumption that vision is responsible for extracting exteroceptive and exproprioceptive information from the environment and can be more externally controlled and studied in a non-invasive laboratory setting than kinesthetic input. The intersegmental dynamics analysis was chosen based on the results of both skilled locomotor behaviour in adults stepping over obstacles (Patla et al., 1994) and infants stepping on a treadmill (Ulrich et al., 1994).

The age of the subjects selected for all three studies ranged from the onset of independent walking to age six. This age-group was chosen based on the learning phases of locomotor behaviour proposed by Bril and Berniere (1992; 1993). The first phase is characterised by the learning of dynamic postural control and it occurs in the first six months of independent walking. Infants are learning how to integrate posture and movement; a coupling required for successful obstacle avoidance. The second phase is characterised by the accurate integration of the available sensory information in order to adjust gait parameters according to environmental demands. In the puzzle metaphor, Patla et al. (1996) assume that the integration of the pieces to form the entire puzzle requires time but occurs in parallel rather than in phases. At the same time that children are integrating posture and movement they are also adjusting their movement to the environmental demands. Thus, the view of the development of locomotion is on a continuum, from the stepping reflex to adult skilled locomotor behaviour. The sculpting and integration of the sensory information with the modulation of the locomotor pattern occur continually over the developmental time course. These processes end when the person is able to consistently deal with environmental demands, such as obstacles. Obstacle avoidance strategies are behavioural manifestations of sculpting and integration of sensory information and locomotor pattern modulation. It was expected that several changes on obstacle avoidance strategies would be observed over this study's age range (from onset to age six of independent walking), reflecting the maturation and integration of the sensory system and the modulation of the locomotor pattern according to the environment.

Study # 1

Kinematic Strategies for Obstacle Avoidance in Children: Role of Exteroceptive Information.

Introduction

Exteroceptive information refers to the identification of locations and features of objects and surfaces in the environment (Gibson, 1979; Gibson, 1982). In this study exteroceptive information refers to the terrain characteristics, specifically the obstacle location and the manipulation of the obstacle properties. The human individual mainly extracts exteroceptive information through the use of vision. Infants and blind people extract exteroceptive information by haptic and auditory input. Children explore the environment, build their affordances and continually update them according to their asymmetric physical growth in order to keep their affordances adjusted to their body scale (Adolph et al., 1993). Body scale refers to the internal representations of the external objects and events accordingly to the subjects body features. When a child has to choose an obstacle avoidance strategies to safely walk in a cluttered environment, his/her decision of which particular strategy may also depend on body scale. The anthropometric characteristics of a child are intrinsic in his/her affordances. Body scale also implies control of action. Affordances are directly detected and guide actions. Thus, obstacle height and width should be based on the anthropometric characteristics of the children in accordance with the notion of affordance.

In this study, obstacle heights and widths were based on the toddler's anthropometric characteristics to respect the notion of affordance. It was expected that the obstacle avoidance strategies would change during the development course. This could indicate that the participants are learning to perceive affordances and acting accordingly.

Considering the background review of the development of the visual system and the sensori-motor integration, the purpose of this study was to investigate the development of obstacle avoidance strategies in children when they are stepping over obstacles of different height and width. In order to address this issue, exteroceptive information was manipulated by combining obstacle height and width. The primary questions for this experiment were: a) does walking experience influence obstacle avoidance strategies (i.e., limb trajectories over obstacles)? b) are there different variables (i.e., subject anthropometrics, developmental characteristics, obstacle features, etc.) that can explain or predict the obstacle avoidance strategies selected?

Methods

Subjects

Twenty-five children participated in the present experiment. Children, ranging in age from one to six years, were recruited from the Kitchener and Waterloo communities. Based on parent's report, no child had any known visual deficits, neurological disorders or musculoskeletal impairments. The gender, chronological age, walking experience, and hip height for each child were recorded and are presented in Table 1. Chronological age ranged from 12 to 70 months. Walking experience, defined as the number of months of independent walking, ranged from 2 to 58 months.

Procedures

Each child was instructed to walk and step over a white foam obstacle placed in his/her travel path, a gray carpet (4.83 m. long and 3.62 m. wide). The expected behaviour was demonstrated once by the investigator at the start of the data collection. Initial starting position, established using footprint cutouts, was identical for each child. The distance from the footprint cutouts to the obstacle was 1.90 m. Exteroceptive information was manipulated using a combination of two different obstacle heights and two different obstacle widths, providing four distinct conditions (Refer to Table 2).

A solid piece of foam was selected as an obstacle based on the pilot study. Two children brought into the laboratory for pilot testing refused to step over both the height adjustable and the fragile obstacles. When they were asked for their preference, they chose a solid piece of foam. Considering this limitation, the present study was planned then to manipulate obstacle height and width.

Table 1. Subject characteristics: gender, chronological age, walking experience, hip height, body weight and total number of trials each child performed (NA stands for not available).

Subject	Gender	Chronological Age (months)	Walking Experience (months)	Hip Height (cm)	Weight (kg)	Failure Rates (%)	Lead Leg Preference (%)	Trials (#)
A	F	23	12	35.2	10	0	75	6
B	M	27	11	39.2	15	54	76.5	25
C	F	36	24	47.3	17	25	26.9	25
D	M	60	47	57	16	4	66.7	26
E	F	46	35	50.1	17.3	4	44	25
F	M	25	16	41.3	14.3	8	63.6	12
G	M	45	34	48.8	15.9	30	47.6	27
H	F	56	43	50.3	18.6	19	76	25
I	F	31	14	39.3	13.2	4	36	25
J	F	36	26	43.2	16.4	33	30.4	27
K	M	60	50	52.2	21.4	13	13	28
L	M	43	31	44.1	15	22	11.1	26
M	F	41	30	43.6	16.1	20	28.6	25
N	M	69	54	62.5	25	12	52	25
O	M	54	37	53.4	18.3	20	37.5	25
P	M	34	25	42.1	16.3	4	83.3	25
Q	M	70	58	56.6	24.5	16	56	25
R	F	16	4	NA	13	NA	NA	0
S	F	26	13	38	14.1	24	50	26
T	M	42	30	42.6	16.6	0	45.8	25
U	M	12	2	NA	NA	NA	NA	8
V	F	43	31	NA	15.9	NA	NA	0
W	M	49	38	NA	NA	NA	NA	6
X	F	12	5	NA	13.2	NA	NA	7
Y	F	16	2	NA	NA	NA	NA	0

The height and width of each obstacle was determined from anthropometric measures of leg length and foot length obtained from 18 children of different age (grouped from onset to 16 months, 17 to 32 months, and 33 to 58 months of independent walking).

The two obstacle heights for each age group were set to the average ankle and mid-shank height of the children measured in that respective group. The two obstacle widths for each age group were set to 40% and 80% of the average foot length. Table 2 shows the different obstacles used for each age group. Thus, the actual height and width of each obstacle were scaled according to the anthropometric measures and varied depending on the walking experience of the child age group. Thus, obstacles were allocated for each child according to their walking experience. The manipulation of obstacle height and obstacle width was done primarily to compensate for presumed differences in body anthropometrics across the developmental perspective.

Table 2. Obstacle features for each age group based on walking experience.

	Age Group 1 (onset to 16 months of independent walking)		Age Group 2 (17 to 32 months of independent walking)		Age Group 3 (33 to 58 months of independent walking)	
Obstacle #	Height (cm)	Width (cm)	Height (cm)	Width (cm)	Height (cm)	Width (cm)
1	4.1	5.4	4.1	5.4	5.4	7.0
2	12.0	5.4	14.6	5.4	15.9	7.0
3	4.1	10.2	4.1	11.1	5.4	14.0
4	12.0	10.2	14.6	11.1	15.9	14.0

Detailed locomotor changes required for obstacle avoidance were assessed using an on-line OPTOTRAK motion analysis system (Northern Digital, Canada). Seven infra-red emitting diodes (IREDs), sampled at 60 Hz, were placed on the right hip, right knee, right ankle, right heel, right toe, left hip and left toe, to monitor limb trajectory over the obstacle. Twenty-five completely randomized trials were performed: five trials for each obstacle condition and five trials with no obstacle. Video recording with a split screen two-camera system was also done to qualitatively document each child's performance.

Data Analyses

Obstacle Avoidance Strategies: Qualitative Video Analysis.

A qualitative assessment of the obstacle avoidance strategies employed by each child was determined through video analysis. Obstacle avoidance success and failure rates, as well as alternative strategies selected, were the three main categories used to describe and classify each child's performance. A trial was considered a success if the child stepped over the obstacle without contacting the obstacle with either the leading or trailing limb. Conversely, a trial was considered a failure if the child contacted the obstacle in any manner (i.e., hit, kicked, or stepped on the obstacle). A trial was classified as an alternative strategy if the child avoided the obstacle by walking around it or if the child required assistance when stepping over the obstacle (i.e., held investigator's hand). Table 1 presents the failure rate percentage of the total number of trials performed for each child.

Leading leg preference was also determined through video analysis. The percentage of left leg leading related to the total number of trials completed for each child is given in Table 1.

For the qualitative analysis of obstacle avoidance strategies only subjects that refused to participate were eliminated. A total of 19 subjects in 474 trials were qualitatively analysed.

Obstacle Avoidance Strategies: Kinematic Analyses.

Each trial was windowed from leading limb toe-off to trailing limb heel contact. A representative trajectory profile of an individual trial is presented in Figure 2. A computer program was used to interpolate any missing data points using a cubic spline procedure (OPTOFIX, Mishac Kinetics). Data were filtered at 6 Hz and the selected kinematic parameters were then calculated.

Many dependent variables could be selected from the limb's trajectory profiles when stepping over the obstacle. Key kinematic gait parameters measured included:

1. lead limb toe clearance (LTCL): represents the safety margin over the obstacle. This dependent measure is important because a large safety margin implies avoiding trips and consequently falls. Trips with the leading toe over the obstacle are dangerous because the body centre of mass is moving away from the support base;

2. lead limb hip elevation (LHEL): ipsilateral elevation of the hip facilitates lead limb flexion over the obstacle. However, a larger hip elevation, which is implicated in larger lateral body sway, can compromise the system's stability;

3. trail limb toe clearance (TTCL): as for leading limb, trailing toe clearance also represents the safety margin over the obstacle. The risks for falls after tripping with the trailing limb are smaller than for leading limb because the body centre of mass is moving

toward the base of support. However, the trailing limb and the obstacle are out of sight and vision cannot provide on-line corrections;

4. foot placement of lead limb before the obstacle at toe-off (FTPL): represents stride adjustments prior to the obstacle.

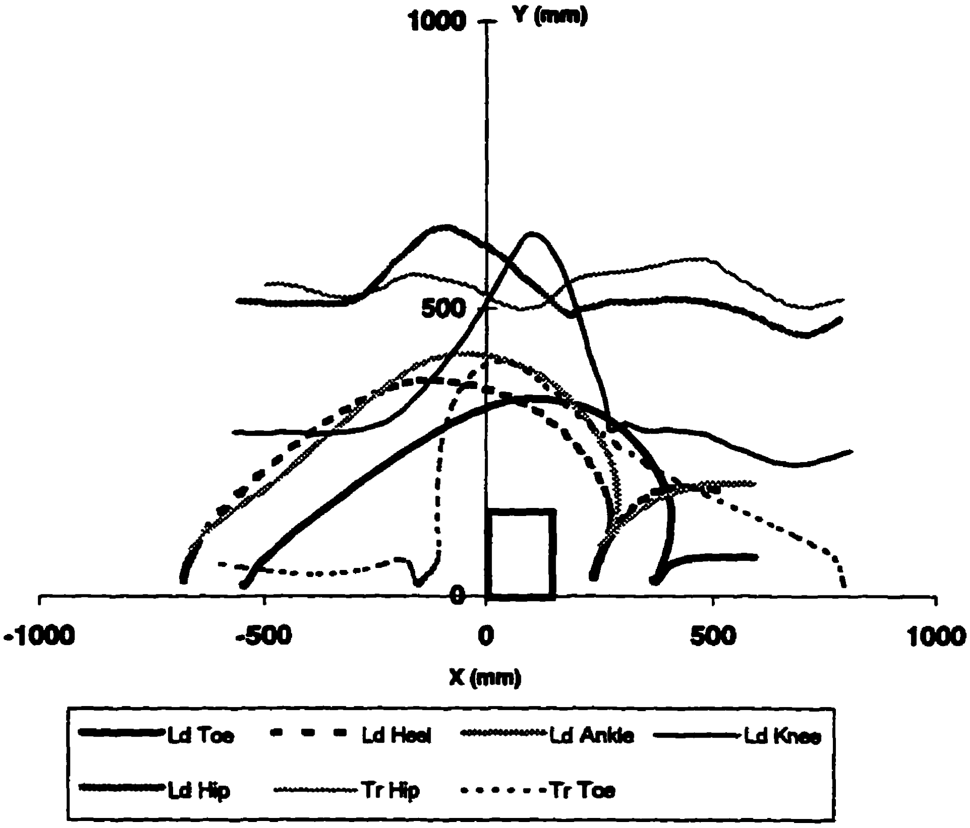

Figure 2. A representative trajectory profile of an individual subject (H) stepping over Obstacle # 4 (Ld refers to leading limb; Tr refers to trailing limb).

Figure 3 graphically illustrates the method by which these variables were determined.

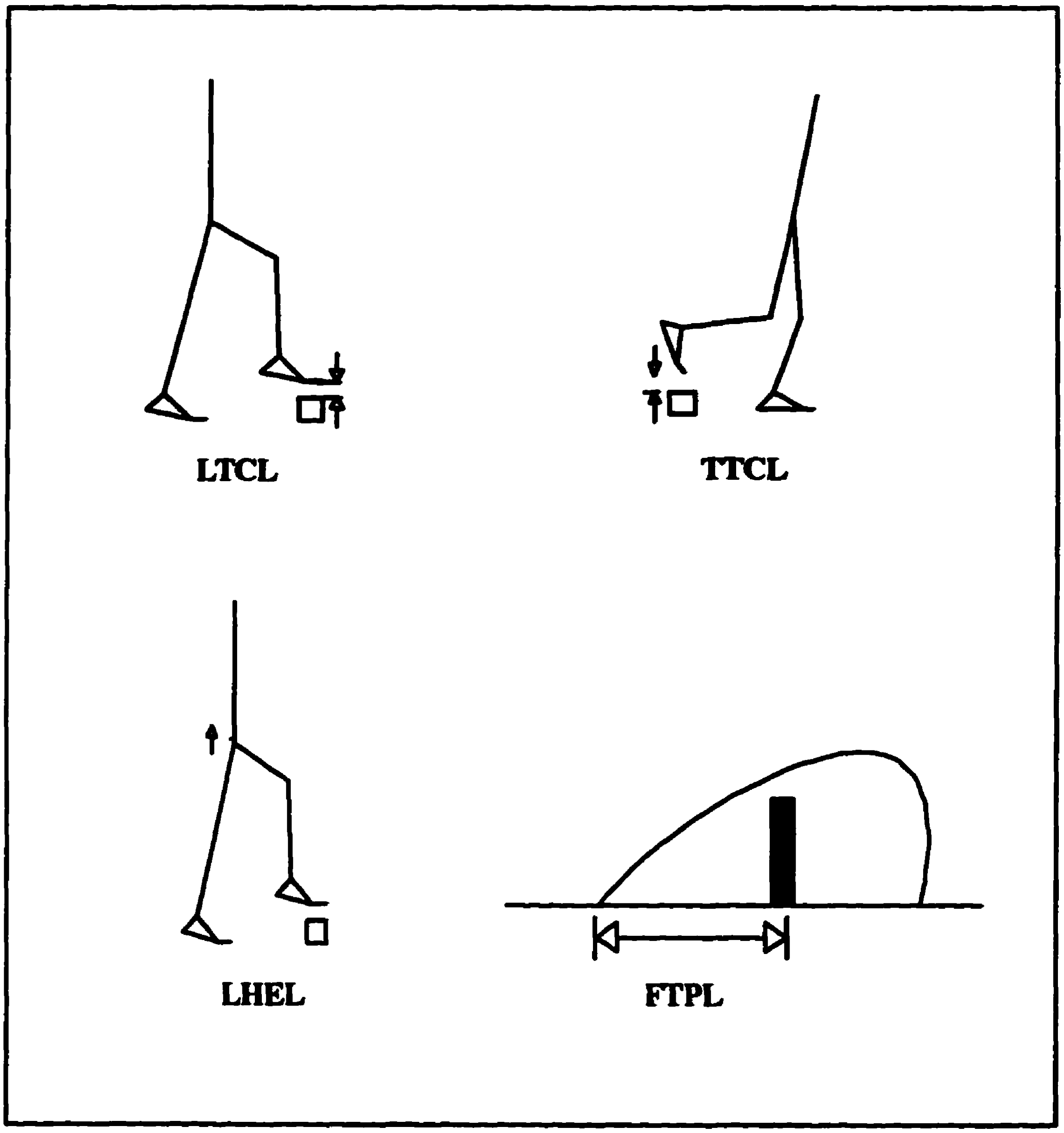

Figure 3. Schematic representation of the kinematic measures: lead limb toe clearance (LTCL), lead limb hip elevation (LHEL), trail limb toe clearance (TTCL), foot placement of the leading limb before the obstacle at toe-off (FTPL).

The kinematic parameters were analysed for a total of 406 successful trials for 19 children. Trials where the child failed to successfully step over the obstacle and trials where the child avoided the obstacle by walking around it were eliminated from the kinematic analysis.

Statistical Analyses

A multiple regression analysis was chosen based on the sample distribution along the walking experience continuum. With the previous distribution of the sample according to age group, a non-homogeneous disparity of children in each age group was observed. The chosen statistical analysis can offer more insight about the influence of independent variables on dependent measures.

A multiple regression analysis was performed for each dependent measure and for each obstacle. The backward elimination procedure was selected as the significance level for each independent measure to fit the model ($p < 0.10$). A Cp procedure was performed to confirm the best model for each dependent variable. Both procedures, backward elimination and Cp were chosen because they account for any colinearity of the independent measures.

Independent variables were grouped into the following categories: anthropometric variables, AV, which are intrinsic to the subject's body (i. e., body mass, hip height and gender); developmental features, DF, which reflect maturation and learning processes (i. e., chronological age and walking experience); exteroceptive information, EI (i.e., obstacle height and width); selected strategies, SS, which represent the subject's decision for a particular pattern to step over the obstacle (leading leg, leading foot placement before the obstacle, leading hip elevation and failure rate).

A generalised linear model (GLM) was conducted to examine the effects of between- and within-subject independent variables on each dependent measure. The GLM procedure allows categorical and continuous variables to be included in the model. In this study, gender and leading leg were considered as categorical variables. All other variables were considered continuous. The variables that were significant in the multiple regression analyses were included in the GLM procedure for each dependent measure with an acceptable level of significance at $p \leq 0.05$. The GLM procedure also allows the determination of a specific mean square error to test the null hypothesis, which is necessary in unbalanced models. The total number of trials performed by each child (Table 1) reveals that the present study has an unbalanced design. Between-subject comparisons were performed with subject as error term and within-subject comparisons had trials as error term after the exclusion of all specific subject effects. A sample of the multiple regression and GLM procedure are presented in Appendix A.

Results

In the Appendix B, means and standard deviations by subject for each kinematic variable are presented. The correlation matrices for each obstacle are presented in Appendix C.

Developmental Features: The statistical comparison across obstacles revealed that chronological age significantly affected foot placement at toe-off before the obstacle ($F_{1,13}$= 4.68, p = 0.05, Figure 4). Among the multiple regression results by obstacle, chronological age predicted trailing toe clearance at obstacle # 1; leading hip elevation at obstacle # 2; and trailing toe clearance and foot placement before the obstacle at obstacle # 3 (Appendix C). Walking experience did not significantly affected any of the dependent measures. However, it is a predictor for leading hip elevation at obstacle # 2.

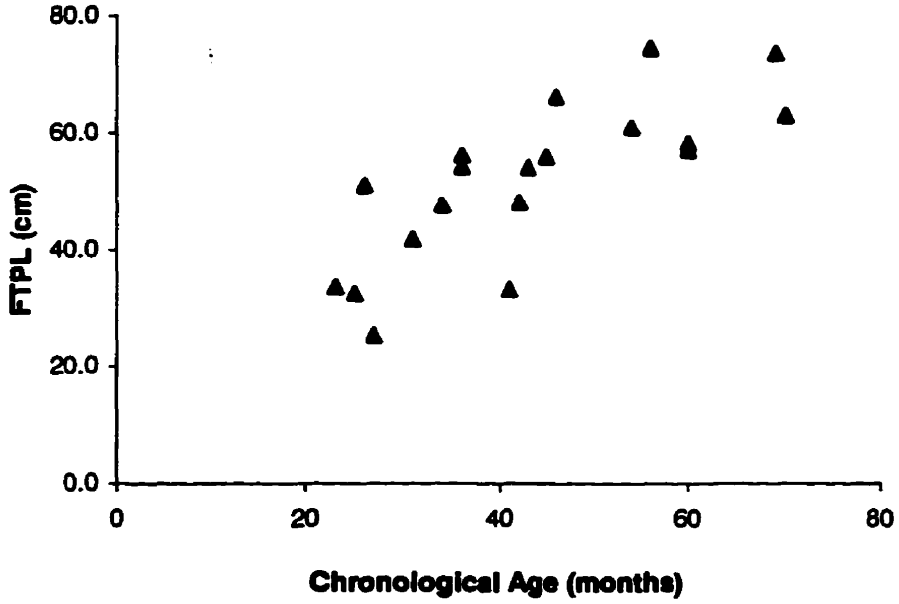

Figure 4: Main effect of chronological age on foot placement at toe-off prior to the obstacle (FTPL).

Anthropometric Variables: Body mass significantly affected trailing toe clearance ($F_{1,12}$ = 12.81, p = 0.004, Figure 5) and foot placement at toe-off prior to the obstacle ($F_{1,13}$ = 18.31, p = 0.0009, Figure 6) as the statistical comparison across obstacles showed. Two interactions were statistically significant: body mass and leading toe clearance on trailing toe clearance ($F_{1,287}$ = 13.04, p = 0.0004, Figure 7); and body mass and obstacle height on leading foot placement before the obstacle ($F_{1,274}$ = 4.29, p = 0.04, Figure 8). Body mass was a predictor for leading and trailing toe clearance and foot placement before the obstacle at obstacle # 1; and leading hip elevation at obstacle # 2 (Appendix C). The multiple regression analyses revealed that hip height explained leading and trailing toe clearance at obstacle # 1; and leading toe clearance at obstacle # 3 (Appendix C). Gender could not affect any of the dependent measures; however, it could predict leading hip elevation at obstacle # 2; and foot placement before the obstacle at obstacle # 3 (Appendix C).

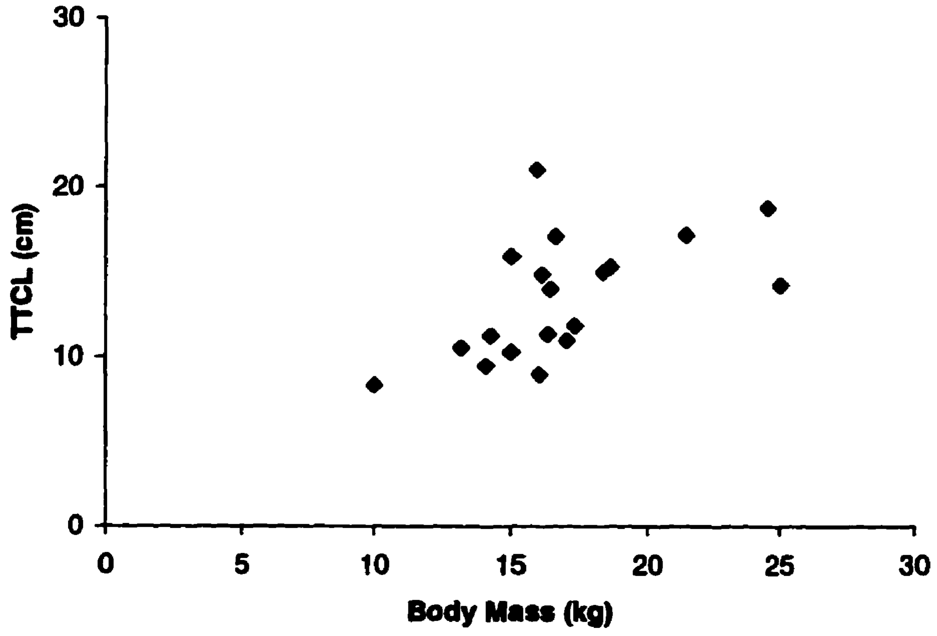

Figure 5: Main effect of body mass on trailing toe clearance (TTCL).

Figure 6: Main effect of body mass on foot placement prior to the obstacle (FTPL).

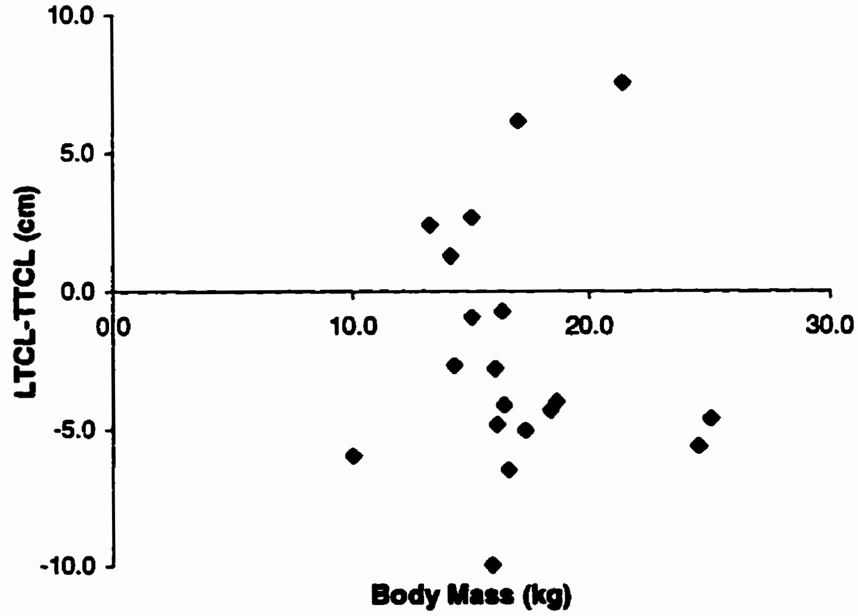

Figure 7: Interaction between body mass and leading toe clearance (LTCL) on trailing toe clearance (TTCL).

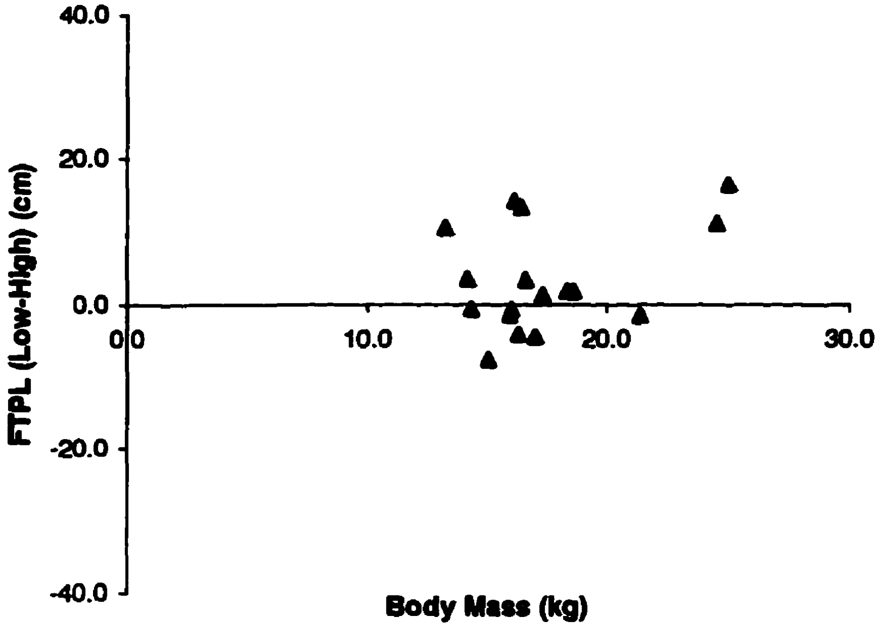

Figure 8: Interaction between body mass and obstacle height on foot placement before the obstacle (FTPL).

Exteroceptive Information: The statistical comparison across obstacles revealed two main effects of obstacle height, first on trailing toe clearance ($F_{1,287} = 24.04$, $p = 0.0001$, Figure 9); and second on leading hip elevation ($F_{1,272} = 20.01$, $p = 0.0001$, Figure 10). Two interactions were also observed: obstacle height and leading hip elevation on leading toe clearance ($F_{1,279} = 4.52$, $p = 0.03$, Figure 11); and obstacle height and leading toe clearance on trailing toe clearance ($F_{1,287} = 5.22$, $p = 0.02$, Figure 12). The Multiple Regression Analyses showed that obstacle height explained leading and trailing toe clearance and foot placement before the obstacle at obstacle # 1; trailing toe clearance, leading hip elevation and foot placement before the obstacle at obstacle # 2; and foot placement before the obstacle at obstacle # 4 (Appendix C). Obstacle width, according to the Multiple Regression Analyses, explained leading hip elevation at obstacle # 2 (Appendix C).

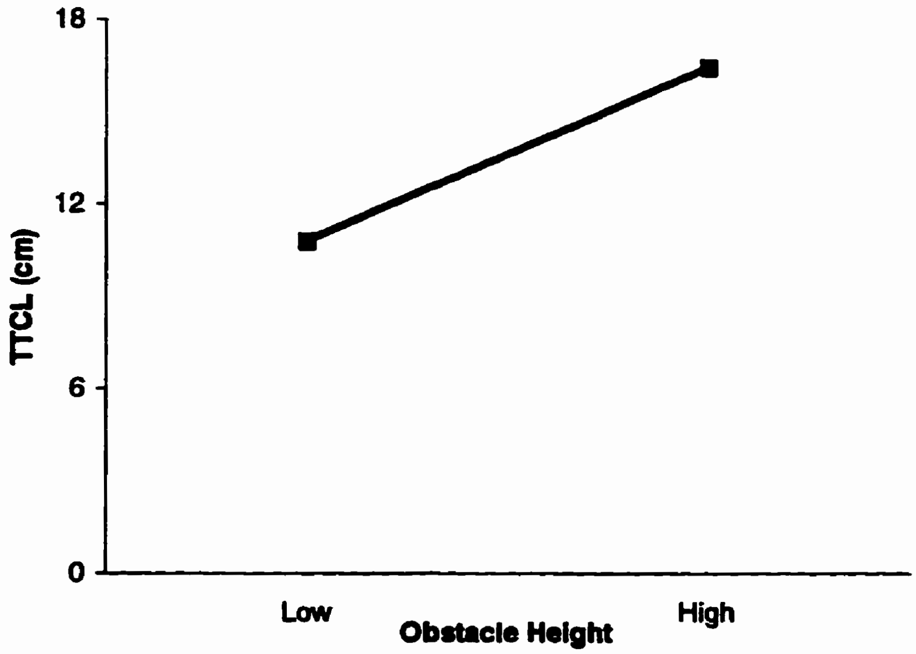

Figure 9: Main effect of obstacle height on trailing toe clearance (TTCL).

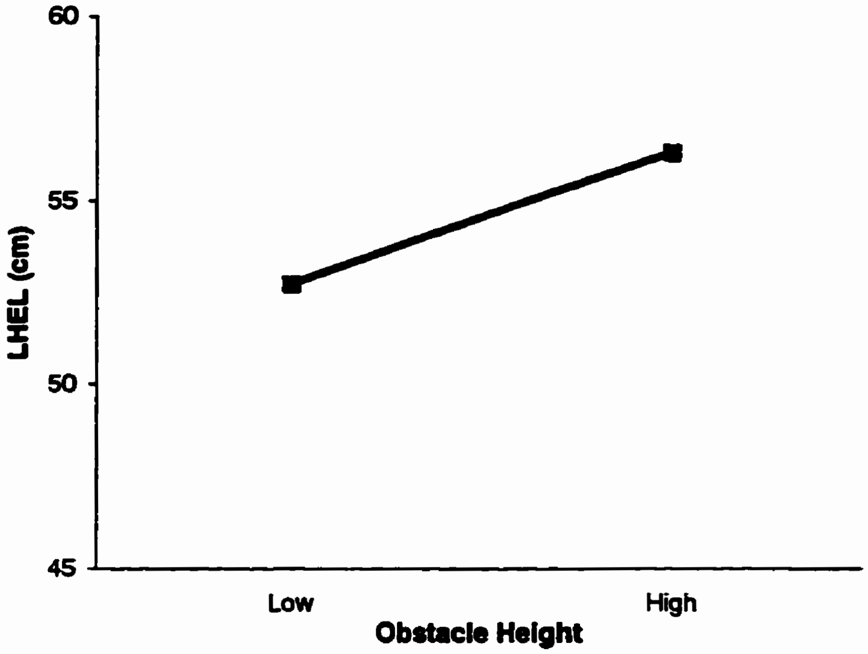

Figure 10: Main effect of obstacle height on leading hip elevation (LHEL).

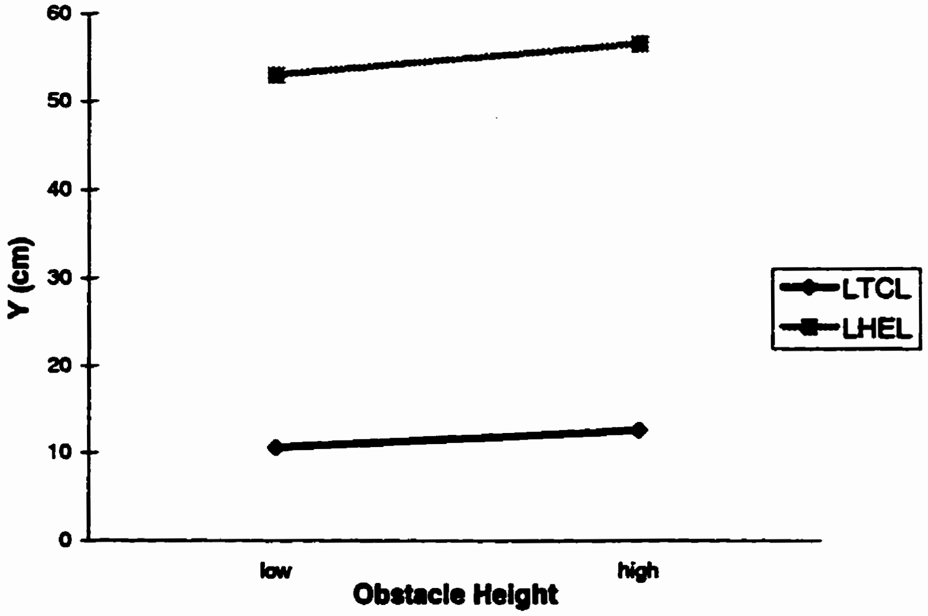

Figure 11: Interaction between obstacle height and leading hip elevation (LHEL) on leading toe clearance (LTCL).

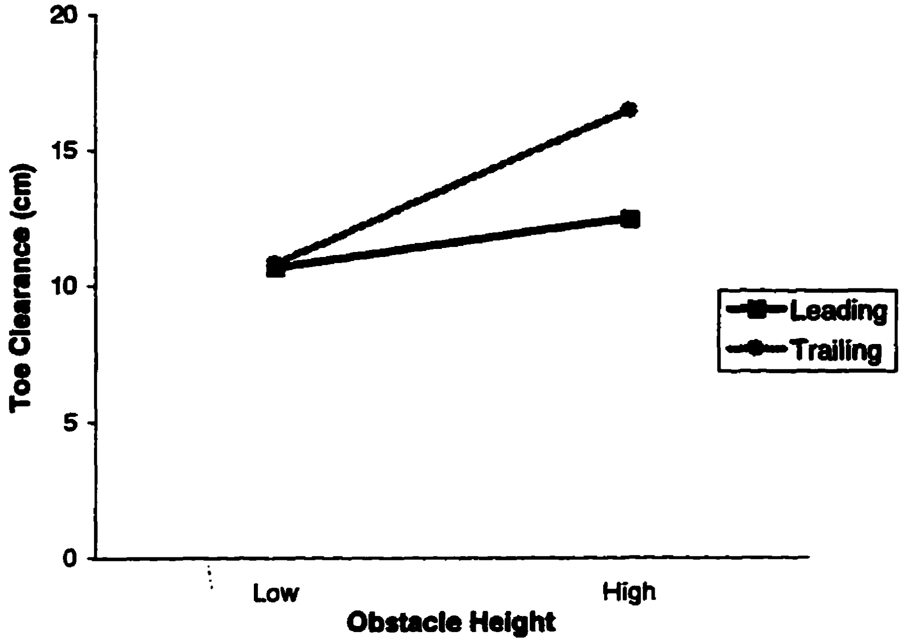

Figure 12: Interaction between obstacle height and leading toe clearance on trailing toe clearance.

Subject Strategies: The statistical comparison across obstacles revealed that leading leg preference had a main effect on trailing toe clearance ($F_{1,279} = 5.52$, $p = 0.02$, Figure 13); another main effect of leading leg preference on leading hip elevation ($F_{1,272} = 12.28$, $p = 0.0005$, Figure 14). The Multiple Regression Analyses showed that leading leg preference explained leading and trailing toe clearance at obstacle # 1; leading toe clearance and leading hip elevation at obstacle # 2 and # 3; and leading toe clearance at obstacle # 4 (Appendix C). A main effect of leading toe clearance on trailing toe clearance ($F_{1,287} = 17.96$, $p = 0.0001$, Figure 15) and leading toe clearance on leading hip elevation ($F_{1,272} = 12.28$, $p = 0.0005$, Figure 16) were also observed. The Multiple Regression Analyses revealed that leading toe clearance predicted leading hip elevation at obstacle # 1; and trailing toe clearance and leading hip elevation at obstacle # 3 (Appendix C). Leading hip elevation explained leading toe clearance at obstacle # 3; and failure rates predicted trailing toe clearance at obstacle # 1; and leading toe clearance and leading hip elevation at obstacle # 3 (Appendix C).

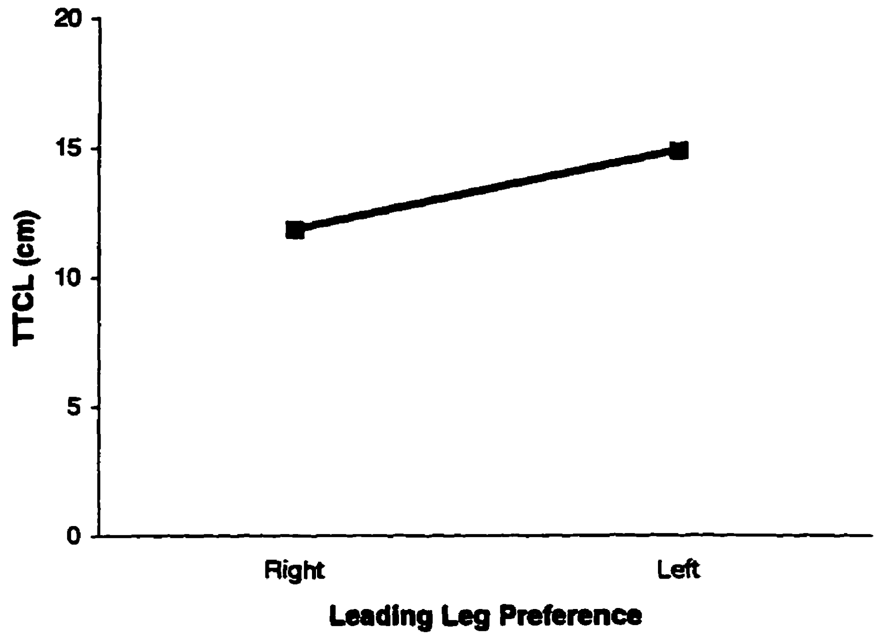

Figure 13: Main effect of leading leg preference on trailing toe clearance (TTCL).

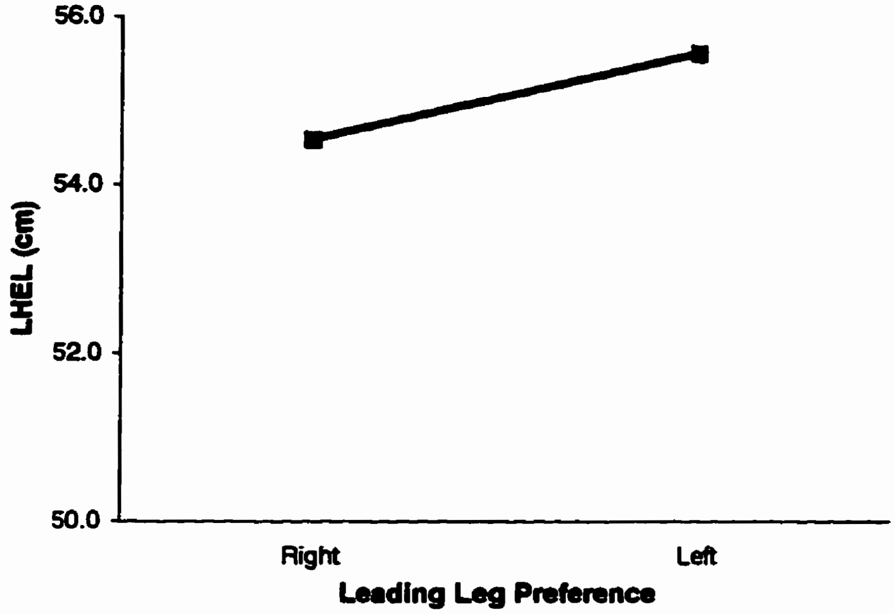

Figure 14: Main effect of leading leg preference on leading hip elevation (LHEL).

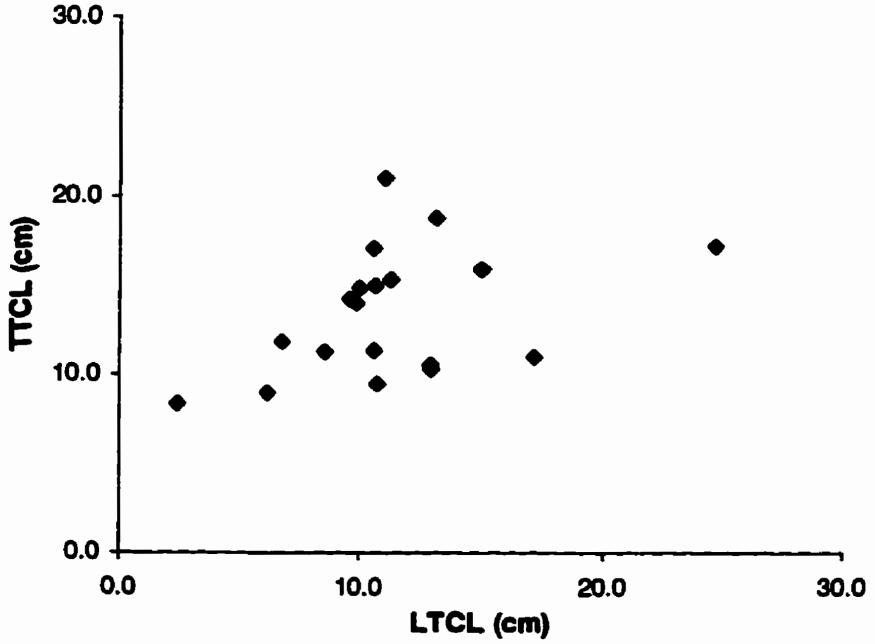

Figure 15: Main effect of leading toe clearance (LTCL) on trailing toe clearance (TTCL).

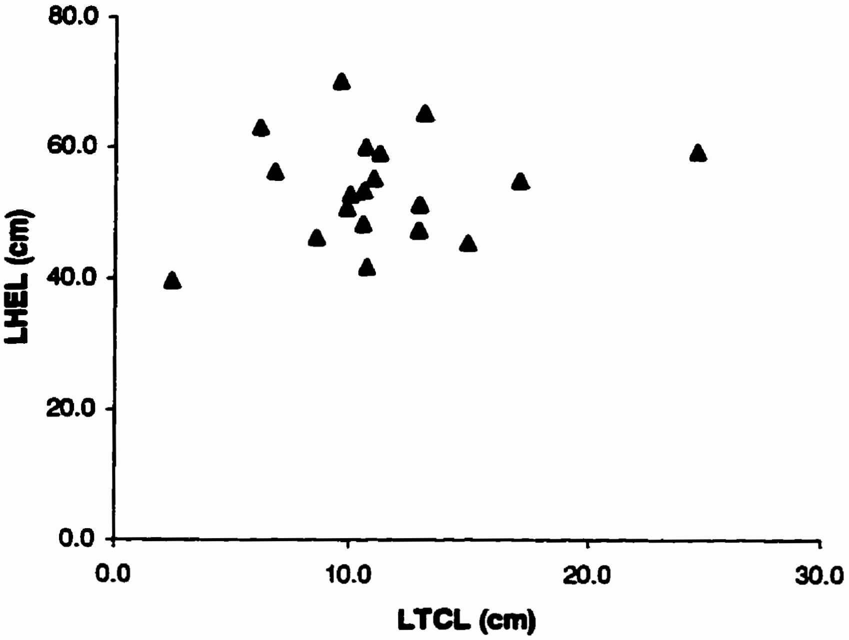

Figure 16: Main effect of leading toe clearance(LTCL) on leading hip elevation (LHEL).

Discussion

When a child faced the experimental set up and was asked to walk from one end of the carpet to another stepping over a foam obstacle, they had several choices: refuse, go around, ask for guidance, purposely step on the obstacle to see what happens or step over the obstacle as demonstrated. Even though the obstacles were body scaled within each age group, they were not customised for each child. Over 16 months, the differences in body characteristics and experience between children are notable. Since the body features and skills change dramatically and the obstacles were not customised, errors can also occur.

Growth and Development: The results of this study revealed a developmental trend in the use of hip hiking for modulating the leading limb elevation. Hip joint elevation was used to raise the toe over the obstacle. This strategy supports the proximo-distal principle in the development of motor control, in which the control of proximal joints by the central nervous system occurs before the control of distal joints. However, this strategy compromises the system stability since balance control is still in the process of development.

Leading toe clearance represents the safety margin over the obstacle and it is important because a large safety margin avoids trips and consequently falls. Trips with the leading toe over the obstacle can be serious since the body's center of mass is moving away from the support base at that time. Considering that chronological age and leg length are closely related (r=0.95) between 1 and 7 years of age (Sutherland. et al., 1988), the variability in leading toe clearance can be attributed to maturation and experience.

Thelen and collaborators (Thelen, 1990a; Thelen et al., 1990b; Thelen et al., 1987; Ulrich et al., 1991; Thelen et al., 1994) have showed that the motor development includes cooperative interactions of many subsystems, such as physical growth. The anthropometric measures, specially body mass can affect the strategies selected. Of note is the variable hip height, which is positively correlated with step length in children (Sutherland. et al., 1988), was negatively correlated with leading toe clearance (as hip height increased leading toe clearance decreased, in obstacles # 1 and 3). This also indicated that the system is modulating the hip joint to promote a more stable strategy to clear low obstacles, the less challenging ones.

Leading hip elevation increased with age and decreased with walking experience. Following the proximo-distal principle of developmental control, the central nervous system should develop the control of hip first than the control of knee and ankle. Thus, motor experience can be a better predictor for hip control than chronological age. Experience can directly improve hip control to guide the movement of the extremities. On the other hand, chronological age which is also positively correlated with body mass and leg length (Sutherland et al., 1988), seems to be related with the maturational aspects of the components of the effector system instead of their integration with the sensory information. Since leading hip elevation facilitates toe clearance, the central nervous system should control the muscles around the hip joint and the displacement of the limb extremity would occur in a more economical way. It can reflect, as speculated in our preliminary study (Patla et al., 1996), an inability to exploit the passive intersegmental dynamics to achieve limb flexion over the obstacle. A kinetic analysis of the swing limb over the obstacle was performed in Study # 3 to address this issue.

Affordances: The failure rate values, as shown in Table 1, indicate that the children were generally able to step over the obstacle successfully. The absence of developmental trends in failure rates indicates that children were able to perform the task but their system performance is not yet robust, i.e., children need to tune their limb trajectories to safely clear the obstacle. These results support the notion of affordances.

The visual or tactile exploratory activity and its refinement are components of the learning process to perceive affordances (Gibson, 1988; Gibson et al., 1987). Since the young kids in this study had been exploring the environment for more than two years and they had more than a year of locomotor experience, they were able to perceive the affordances for this task but they were not able yet to successfully and consistently guide their action. In contrast, older children, after 35 months of walking experience did not have failure rates greater than 20%. These small errors can also be attributed to distracting events or result from exploration of a new way to perform the task. Thus, the poor limb trajectory modulation is an indicator of behavioural regression observed in postural control (Shumway-Cook et al., 1995; Bronstein et al., 1996), in locomotion on slopes (Adolph, 1995) and in a descriptive study on obstacle avoidance in children (Rosengren et al., 1994).

Older children rarely stepped around the obstacle or required assistance to step over the obstacle. In contrast, younger children had higher percentages of alternative obstacle avoidance strategies. Children with less than 10 months of independent walking were very smart, they always avoided the obstacle by going around it. This result revealed that children with small amount of walking experience can perceive actions afforded by the obstacle. The results also showed that young children have a internal representation of their body limitations which can compromise postural stability. Children between 11 and 25 months of walking experience consistently asked for assistance when stepping over the obstacle. Considering that the time in single-limb support during the flat ground gait cycle in children approaches the adult level at age of 3.5 years (Sutherland et al., 1988), children in this study that asked for assistance when stepping over the obstacle revealed lack of ability to control the body mass in the single support phase. Assistance provided decreased the balance demands as the child steps over obstacle. Rosengren and Wells (1994) also observed similar postural adjustments when 3- to 4-year-old children stepped over obstacles. Their children raised the arms and leaned forward over the obstacle. In this study, the examiner was usually beside the child during the walking trial to prevent falls. Young children smartly utilized the examiner's hand as another source of support and avoided single limb support at the obstacle. In doing that children showed a rudimentary sensory-motor transformation. However, when children successfully stepped over the obstacle and the kinematic measures could be interpreted, children were able to modulate the proximal joint (hip) (Figure 10) and the trailing toe to clear the obstacle (Figure 9) according to the obstacle height. These results indicate that in general children in this age range are able to perceive affordances for locomotion over uneven terrain; but, compared with adults (Patla et al., 1992b; Patla et al., 1993a; Patla et al., 1995b), they poorly modulate their limbs either over raising the trailing limb or compromising stability by elevating the leading hip more than necessary.

Exteroceptive Information: Children in this study used exteroceptive information to perform the task. Obstacle height affected trailing toe clearance and leading hip elevation (Figure 9 & 10). Leading hip elevation is important to facilitate limb flexion over the obstacle (Patla et al., 1996) and its interaction with obstacle height indicate that children in this study were maintaining a stable contribution of hip hiking to limb elevation. Larger toe clearance while representing a greater safety margin may also be interpreted as immaturity of the visual system (Chandna, 1991; Movshon et al., 1988). Increased toe clearance values as a function of obstacle height revealed similar problems in visual perception in elderly adults and in our preliminary study (Patla et al., 1996). This was confirmed by another study with age-related maculopathy subjects (degeneration of the fovea) (Patla et al., 1995a). Further insight into this issue can be clarified if the contrast between the color of the obstacle and the ground was decreased and/or the room luminance decreased. This was addressed by manipulating the obstacle color in Study # 2.

The location of the leading foot prior to the obstacle reflects the adjustments made in the strides as the child approaches the obstacle. Patla et al. (1993b) observed that leading foot placement before the obstacle is relatively independent of obstacle height in young adults. Children had poorer stride adjustments prior to going over the obstacle, as observed in our preliminary study (Patla et al., 1996). The results of this study revealed that the closer the leading foot was placed near the obstacle, an increase in leading hip elevation was observed. In older healthy adults and adults with visual impairment, a common strategy is to place the lead foot further back from the obstacle, which would give them more time to fine tune their trajectory based on sensory input. Children showed a more robust sensory-motor transformation allowing them to place their lead limb closer to the obstacle. During the first six months of independent walking, children learn how to integrate posture and movement, i.e., dynamic postural control (Bril et al., 1992; Bril et al., 1993). After this time, children learn how to accurately integrate the available sensory information in order to adjust their gait parameters according to environmental demands (Bril et al., 1992; Bril et al., 1993). Future research focusing on the stride adjustments prior to the obstacle in a larger age range is necessary to determine when the adult levels are achieved.

Leg Dominance: Considering that the distance from the start point to the obstacle were fixed for all participants, and step length adjustments were qualitatively observed before the obstacle, children in the present study showed smaller mean values of leading hip elevation when the right leg was leading (Figure 17). However, leading toe clearance values were smaller when left leg was leading for all obstacles (Figure 18).

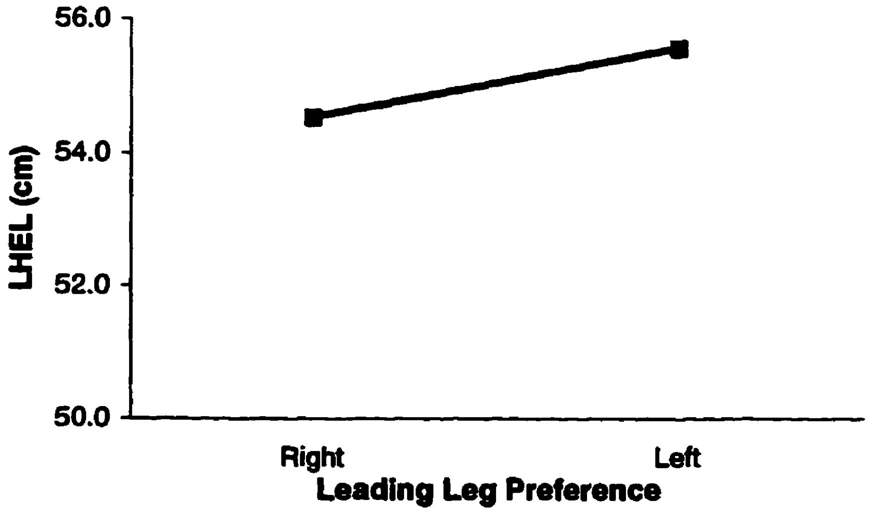

Figure 17. Leading leg preference main effect on leading hip elevation.

For adults, the preferred limb is used to manipulate an object or lead with, while the non dominant limb is used primarily as a stabilizer. Even though, approximately 75% to 90% of the adult population have a strong preference for right side (Gabbard, 1992), recent studies with 3- to 5-year-old reported that 25% to 50% exhibit no preference for one foot over the other (Gabbard et al., 1991; Gabbard et al., 1987). However, a larger study conducted by Sutherland et al. (1988) revealed that the majority of 449 subjects exhibited foot preference measured by kicking at the age of four. With the leading leg preference measure alone, it is not possible to infer that the participants in this study had or had not established foot preference. However, in decreasing toe clearance a child decreased the energy cost and increased the chances to trip and fall. Considering the development of the visual system and the improvements in sensory-motor transformations, a decrease in toe clearance was expected.

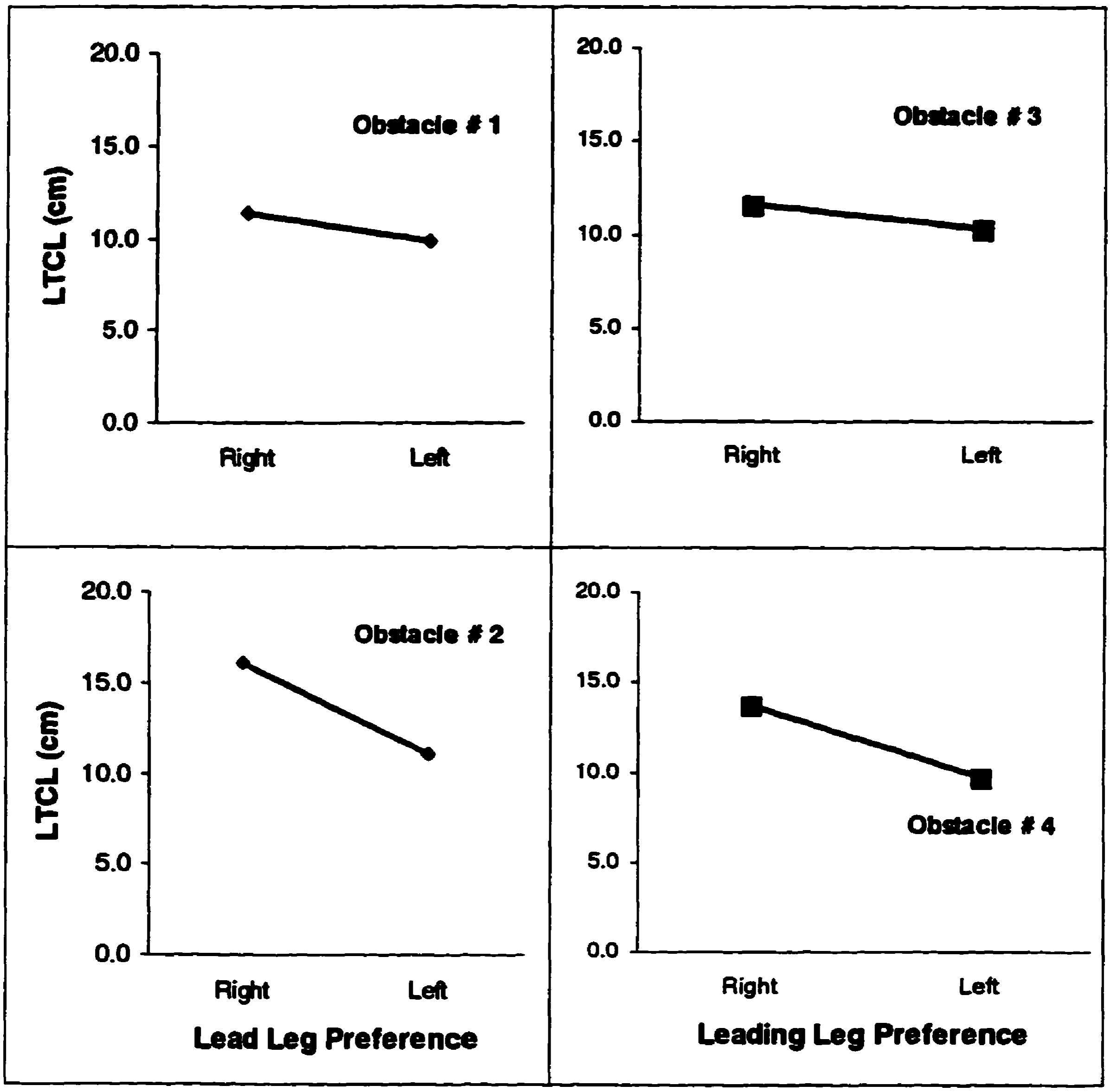

Figure 18. Leading toe clearance according to leading leg preference for each obstacle.

Expproprioceptive Information: Similar leading and trailing toe clearance values were observed in young adults (Patla et al., 1995b; Patla et al., 1993b) and in our preliminary study (Patla et al., 1996). Visual information from the obstacle and the leading limb trajectory over the obstacle plus the kinesthetic input from the leading limb were used by children to modulate the trailing limb. Control of leading and trailing limbs over the obstacle are sensorially coupled. These results give some evidence to support the assumption that children are able to extract exproprioceptive information and act accordingly. However, a definitive proof can be achieved if vision (about limb posture and movements) was restricted for both leading and trailing limbs. This issue was explored in the second study.

Study # 2

Role of exproprioceptive information on swing limb trajectory over obstacles in young children

Introduction

Individuals usually step over obstacles in the travel path with both limbs, one leading while the other is trailing. The trailing limb can not be seen as it travels over the obstacle. Thus, in order for the central nervous system (CNS) to modulate trailing limb trajectory over obstacles, intersensory coupling between the visual and kinesthetic systems is required. Exproprioceptive information refers to the identification of the body parts relative to one another and relative to the objects and events in the environment (Gibson, 1979; Gibson, 1982; Lee et al., 1986). According to Lee and Young (1986), vision is the only sensory system responsible for detecting exproprioceptive cues. During obstacle avoidance, exproprioceptive input provides relevant information about the orientation of the limb and its position and velocity as it goes over obstacles. Thus, exproprioceptive information plays a key role in the control of limb elevation (Patla et al., 1995b) as individuals step over obstacles.

A comparison of leading limb versus trailing limb trajectories can provide insight into the role of exproprioceptive cues in the control of locomotion over obstacles. If the ability to detect exproprioceptive cues is compromised (i.e., through restricted vision), how does the CNS modulate obstacle avoidance strategies in order to successfully clear the obstacle with both the leading and trailing limb. Vision of the limbs can be restricted in numerous ways by asking subjects to wear goggles, a neck collar or to hold an object in front of their body. Subjects may plan in advance adaptive obstacle avoidance strategies several steps prior to the obstacle and/or monitor the leading limb over the obstacle through forward flexion of the neck.

Lack of visual exproprioceptive input results in higher variability in elevation of the toe over obstacles. Patla et al. (Patla et al., 1993b) manipulated exproprioceptive input during obstacle avoidance in young adults who wore goggles. The major finding was related to the compensation by the kinematic parameters (toe clearance and foot placement before the obstacle) of gait when exproprioceptive information was absent. Patla et al. (1995b) analysed how exproprioceptive information affects the kinematic parameters of the locomotion over solid and fragile obstacles in young adults by comparing the leading limb versus the trailing limb. An increase in trail limb toe clearance would be expected, but the subjects did not choose to do that; instead toe clearance results were similar. However, lack of visual exproprioceptive input resulted in higher variability in elevation of the toe over obstacles.

Based on the results of the studies detailed in the introduction and with the challenge to expand our data base, the purpose of this study was to verify the contribution of the exproprioceptive input to tune the kinematic parameters of the gait during locomotion over obstacles. We are expecting a higher toe clearance and more anterior foot placement before the obstacle when the locomotor pattern modulation is based only on the kinesthetic information. We are also expecting to see a pronounced head flexion in the restricted vision condition according to the obstacle height.

Method

Subjects

Twenty children participated in the present experiment. Children, ranging in age from one to six years, were recruited from the Kitchener and Waterloo communities. Sixteen subjects also were volunteers in Study # 1. No child had any known visual deficits, neurological disorders or musculoskeletal impairments, based on self-report of parents. The gender, chronological age, walking experience, eye height, and body weight for each child were recorded and are presented in Table 3. Chronological age ranged from 15 to 73 months. Walking experience, defined as the number of months of independent walking, ranged from 8 to 62 months.

Procedures

Children were instructed to walk and step over a gray foam obstacle placed in their travel path, a gray carpet (4.83 m. long and 3.62 m. wide). The expected behaviour was demonstrated once by the investigator at the start of the data collection. Initial starting position, established using footprint cutouts, was identical for each child. The distance from the footprint cutouts to the obstacle was 1.90 m. Exproprioceptive information was manipulated using a combination of two different obstacle heights and two vision situations, with or without wearing a collar, providing four distinct conditions (Refer to Table 4). The obstacle width was established by the corresponding smaller width in Study # 1. The high obstacle heights were determined in Study # 1 and were maintained in the present study, while the low obstacle height was chosen as corresponding for half of the toe clearance on over-ground walking.

Table 3. Subject characteristics: gender, chronological age, walking experience, eye height, body weight and total number of trials each child performed.

Subj	Gender	Chronological Age (months)	Walking Experience (months)	Eye Height (cm)	Weight (Kg)	Failure Rates (%)	Lead Leg Preference (%)	Trial (#)
A	F	52	41	100.3	19.3	12	14.3	25
B	F	46	34	96	19.5	34	15.8	27
C	F	51	40	101	18.5	0	83.3	26
D	M	26	15	80.2	14.5	33	57.9	26
E	M	51	40	96.9	17.2	8	21	25
F	F	41	31	91.9	17.5	4	25	25
G	M	65	55	104.8	22.7	43	38.5	19
H	M	47	35	106.5	17.3	41	21.4	19
I	F	46	35	95	17.3	11	90	25
J	F	59	46	103.9	20.5	0	40	25
K	F	39	22	86.1	16	26	83.3	23
L	M	73	61	117.4	24.5	0	95	26
M	M	45	33	92.6	16.8	12	80	26
N	F	72	62	107.7	23	8	45	25
O	M	68	55	108.4	24	32	30	25
P	F	30	19	85.8	14	44	65	25
Q	M	73	57	122.5	26.4	27	60	25
R	M	58	41	104.3	30	12	25	25
S	M	38	29	97.5	17.3	33	63.2	25
T	F	15	8	75	13.5	NA	NA	0

Detailed locomotor changes required for obstacle avoidance were assessed using an on-line OPTOTRAK motion analysis system (Northern Digital, Canada). Five infra-red emitting diodes (IREDs), sampled at 60 Hz, were placed above the right eye, left eye, shin, right toe and left toe, to monitor head displacement and limb trajectory over the obstacle. Twenty-five completely randomized trials were performed: five trials for each experimental condition and five control trials. Video recording with a split screen two-camera system was also done to qualitatively document each child's performance.

Table 4. Experimental conditions for each age group based on walking experience.

	Age Group 1 (onset to 16 months of independent walking)		Age Group 2 (17 to 32 months of independent walking)		Age Group 3 (33 to 62 months of independent walking)	
Condition #	Height (cm)	Vision	Height (cm)	Vision	Height (cm)	Vision
1	0.5	Unrestricted	0.5	Unrestricted	0.5	Unrestricted
2	0.5	Restricted	0.5	Restricted	0.5	Restricted
3	12.0	Unrestricted	14.5	Unrestricted	15.9	Unrestricted
4	12.0	Restricted	14.5	Restricted	15.9	Restricted

Data Analyses

Obstacle Avoidance Strategies: Qualitative Video Analysis. A qualitative assessment of the obstacle avoidance strategies employed by each child was determined through video analysis as in Study # 1. For the qualitative analysis of obstacle avoidance strategies only the subjects who refused to participate were eliminated. A total of 19 subjects in 467 trials were qualitatively analysed.

Obstacle Avoidance Strategies: Limb Kinematic Analyses. Each trial was windowed from leading limb toe-off to trailing limb foot contact. A representative trajectory profile of an individual trial is presented in Figure 19. A computer program was used to interpolate any missing data points using a cubic spline procedure (OPTOFIX, Mishac Kinetics). Data was filtered at 6 Hz and the selected kinematic parameters were then calculated.

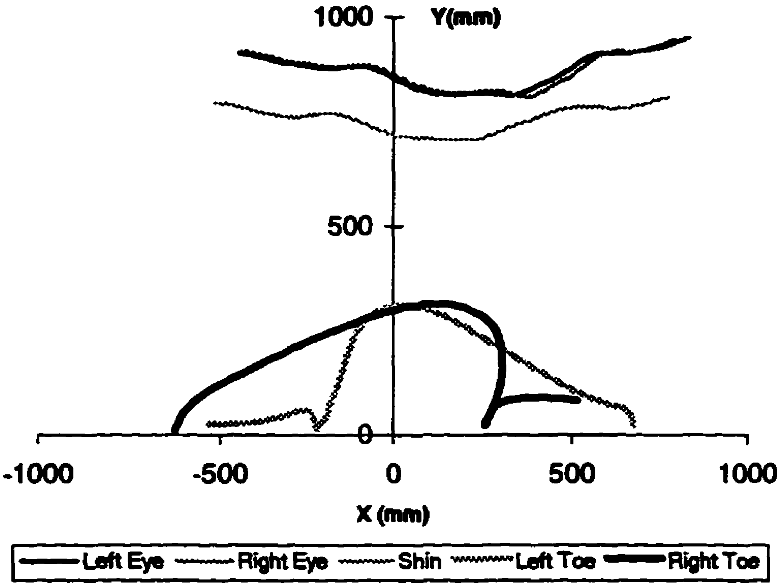

Figure 19: A representative trajectory plot of an individual subject (E) stepping over a high obstacle with restricted vision.

Key kinematic gait parameters measured included:

1. lead limb toe clearance (LTCL)
2. trail limb toe clearance (TTCL)
3. foot placement of lead limb before the obstacle at toe-off (FTPL).

Limb kinematic parameters were analysed for a total of 428 successful trials for 19 children.

Obstacle Avoidance Strategies: Head Kinematic Analyses. Each trial was windowed from the first frame to trailing foot contact after the obstacle. A representative trajectory profile of an individual trial is presented in Figure 19. The data interpolation and filtering followed the same procedure in Study # 1 and the magnitude of pitch motion was then calculated. Each trial was partitioned into four phases as following:

1) Phase 1: from first frame to one full stride before leading toe-off to obstacle;
2) Phase 2: one full stride before leading toe-off to obstacle;
3) Pre-Obstacle Phase: from leading toe-off to toe over the obstacle;
4) Post-Obstacle Phase: from leading toe over the obstacle to trailing foot contact.

Head kinematic parameters were analysed for a total of 336 successful trials for 19 children.

Statistical Analyses

A multiple regression analysis was chosen based on the sample distribution along the walking experience continuum. With the previous distribution of the sample according to age group, a non-homogeneous disparity of children in each age group was observed. The chosen statistical analysis can offer more insight about the influence of independent variables on dependent measures.

A multiple regression analysis was performed for each dependent measure and for each condition. The backward elimination procedure was selected as the significance level for each independent measure to fit the model ($p < 0.10$). A Cp procedure was performed to confirm the best model for each dependent variable. Both procedures, backward elimination and Cp were chosen because they assure that the dependent measure was not affected by the colinearity of the independent measures.

Independent variables were grouped into the following categories: anthropometric variables (AV) are intrinsic to the subject's body (i. e., body mass, hip height and gender); developmental features (DF) reflect maturation and learning processes (i. e., chronological age and walking experience); exteroceptive information (EI) (i.e., obstacle height and width); selected strategies (SS) represent the subject's decision for a particular pattern to step over the obstacle (leading leg, leading foot placement before the obstacle, and failure rate). For the head magnitude of pitch motion, the selected strategies included the magnitude of pitch head motion in all the precedent phases, leading leg preference and failure rates.

A generalised linear model (GLM) was conducted to examine the effects of between- and within-subject independent variables on each dependent measure. The GLM procedure allows categorical and continuous variables into the model. In this study, gender and leading leg were considered as categorical variables. All other variables were considered continuous. The variables that were significant in the multiple regression analyses were included in the GLM procedure for each dependent measure with an acceptable level of significance at $p \leq 0.05$. The GLM procedure also allows the determination of a specific mean square error to test the null hypothesis, which is necessary in unbalanced models. The total number of trials performed by each child (Table 3) reveals that the present study has an unbalanced design. Between-subject comparisons were performed with subjects as error term and within-subject comparisons had trials as the error term after the exclusion of all specific subject effects. A sample of the multiple regression and GLM procedure are presented in the Appendix A.

Results

In the Appendix D, means and standard deviations by subject for both limb and head kinematic variables are presented. The correlation matrices for each limb kinematic by condition are presented in Appendix E. Appendix F presents the correlation matrices for head motion by condition.

Developmental Features: The statistical comparison across conditions revealed that chronological age significantly affected head pitch angle magnitude in phase 2 ($F_{1,15}$= 7.04, p = 0.02, Figure 20); and in post-obstacle phase ($F_{1,14}$= 7.82, p = 0.01, Figure 21). Two interaction between chronological age and walking experience on leading toe clearance ($F_{1,15}$= 3.86, p = 0.07, Figure 22); and on head pitch angle magnitude in pre-obstacle phase were marginally significant ($F_{1,14}$= 3.48, p = 0.08, Figure 23). Among the multiple regression results by condition, chronological age predicted leading and trailing toe clearance, foot placement before the obstacle, and head pitch angle magnitude in pre-obstacle phase in condition 1; failure rates in all conditions; head pitch angle magnitude in phase 1 and condition 2 and 4; trailing toe clearance in condition 3; foot placement before the obstacle in condition 3 and 4; and head pitch angle magnitude in phase 2 and pre-obstacle phase in condition 4 (Appendices E and F). Walking experience explains foot placement before the obstacle in condition 3; head pitch angle magnitude in pre-obstacle phase in condition 1 and in phase 1 and 2 in condition 4.

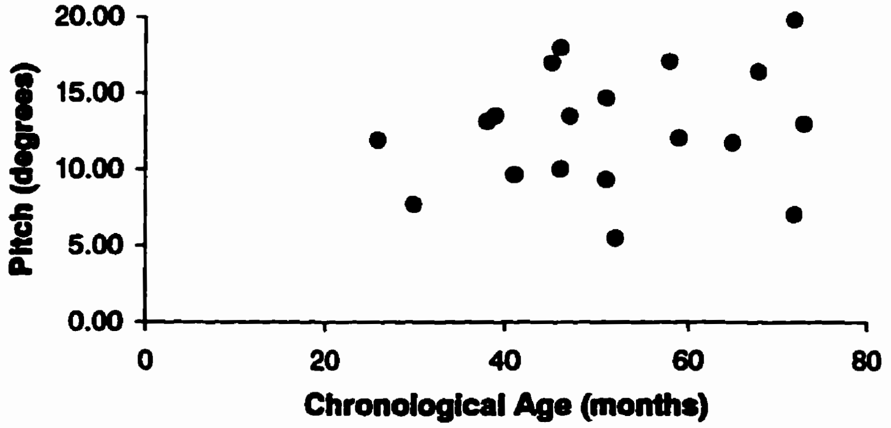

Figure 20. Main effect of chronological age on head pitch angle magnitude in Phase 2.

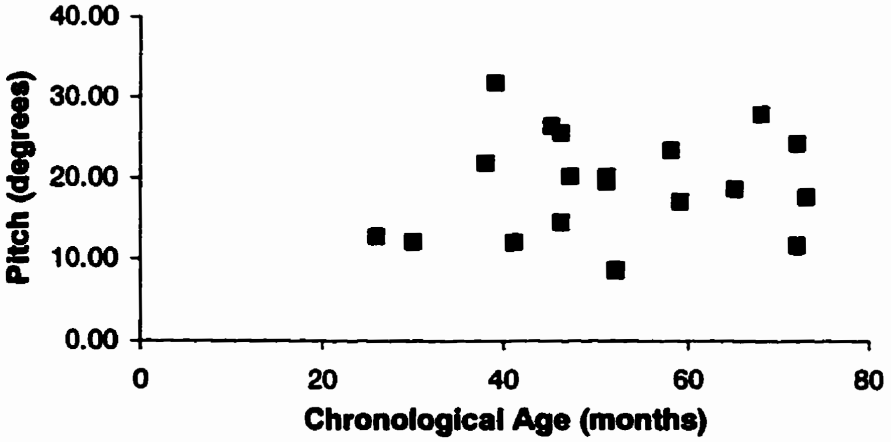

Figure 21. Main effect of chronological age on head pitch angle magnitude in post-obstacle phase.

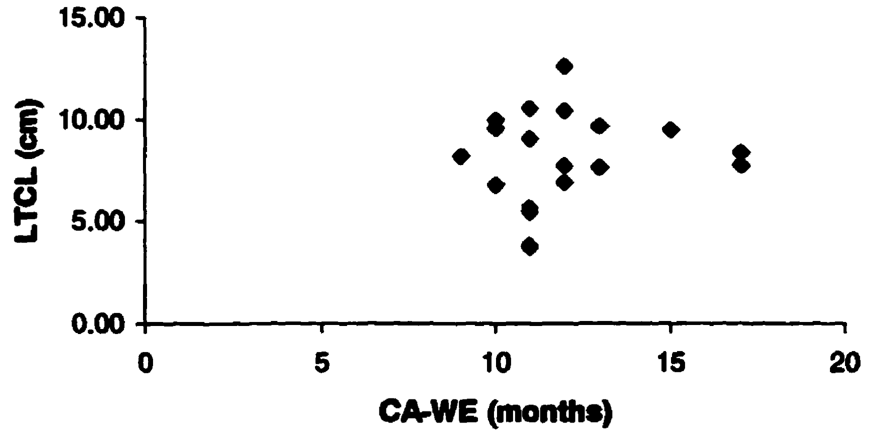

Figure 22. Interaction between chronological age (CA) and walking experience (WE) on leading toe clearance (LTCL).

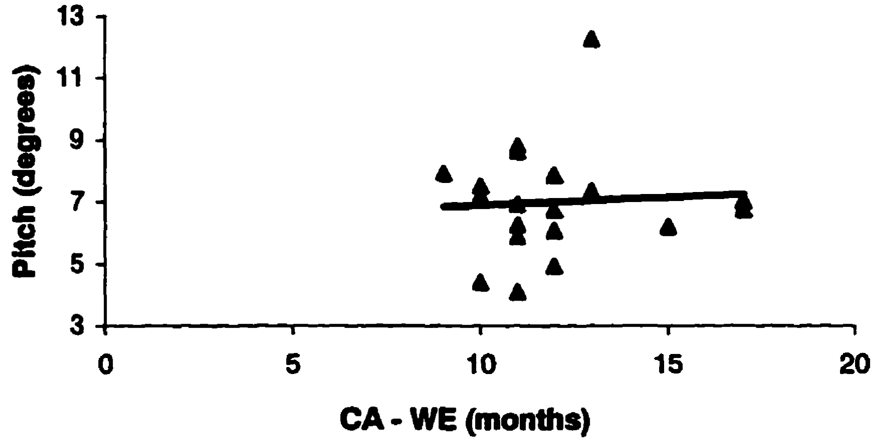

Figure 23. Interaction between chronological age (CA) and walking experience (WE) on head pitch angle magnitude on pre-obstacle phase.

Anthropometric Variables: Body mass significantly affected trailing toe clearance ($F_{1,15}$= 7.75, p = 0.01, Figure 24); and foot placement before the obstacle ($F_{1,14}$= 8.88, p = 0.01, Figure 25) as the statistical comparison across conditions showed. The multiple regression analysis for each condition revealed that body mass predicts leading and trailing toe clearance in condition 1; trailing toe clearance and foot placement before the obstacle in condition 2; failure rates, trailing toe clearance and foot placement before the obstacle in condition 3; and leading toe clearance in condition 4 (Appendix E). Eye height explains the variability in foot placement before the obstacle in condition 1 and 3; trailing toe clearance in condition 4; failure rates in condition 1 and 2; head pitch angle magnitude in pre-obstacle phase in condition 1, in phase 1 in condition 2, and in post-obstacle phase in condition 4 (Appendices E and F). Statistical comparison across condition revealed a main effect of gender on head pitch angle magnitude in phase 2 ($F_{1,15}$= 5.48, p = 0.03, Figure 26). The multiple regression analysis showed that gender predicts trailing toe clearance in condition 4 (Appendix E); head pitch angle magnitude in phase 1 in condition 1, and in phase 2 in conditions 2 to 4 (Appendix F).

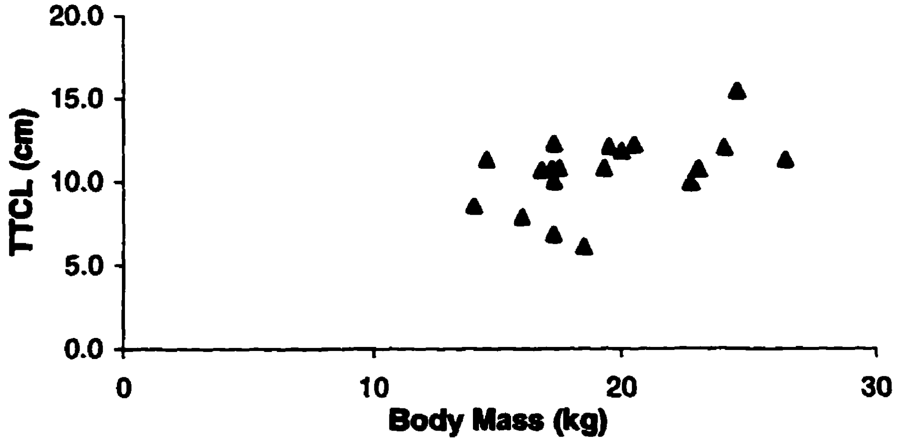

Figure 24. Main effect of body mass on trailing toe clearance (TTCL).

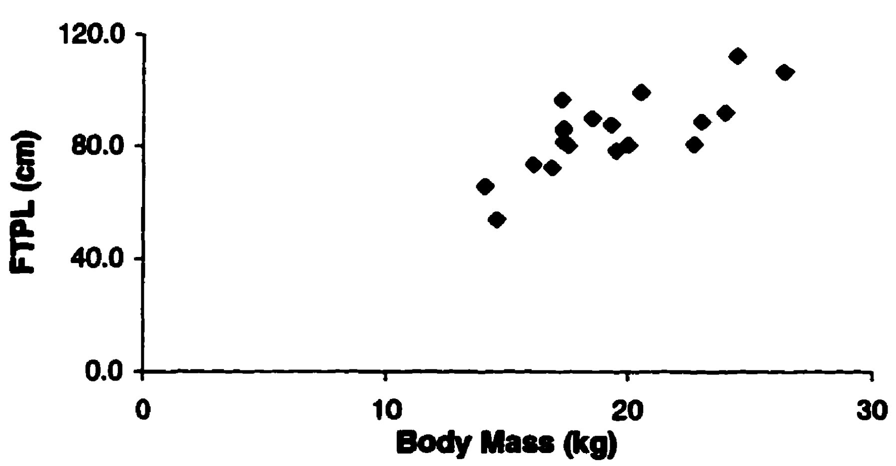

Figure 25. Main effect of body mass on foot placement before the obstacle (FTPL).

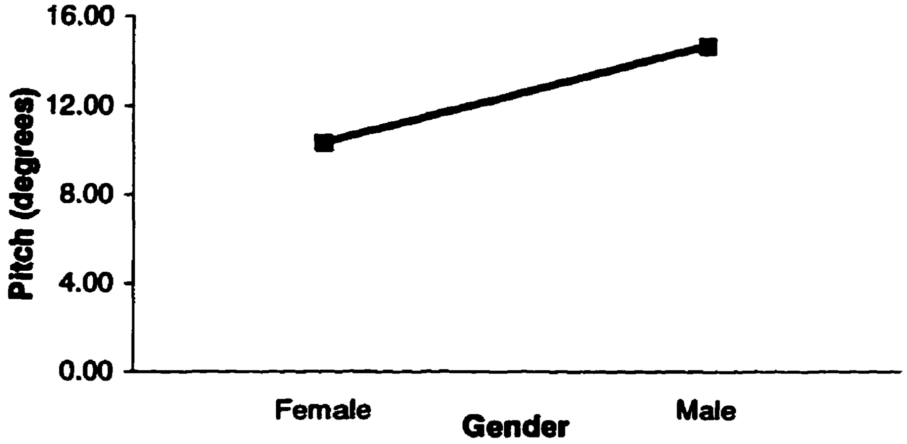

Figure 26. Main effect of gender on head pitch angle magnitude in phase 2.

Exteroceptive Information: The statistical comparisons across conditions revealed main effects of obstacle height on leading toe clearance ($F_{1,413}$= 209.93, p = 0.0001, Figure 27); on trailing toe clearance ($F_{1,381}$= 230.70, p = 0.0001, Figure 28); on foot placement before the obstacle ($F_{1,381}$= 63.24, p = 0.0001, Figure 29); on head pitch angle magnitude in post-obstacle phase ($F_{1,318}$= 32.01, p = 0.0001, Figure 30). An interaction between leading leg preference and obstacle height on leading toe clearance ($F_{1,413}$= 8.04, p = 0.005, Figure 31) was observed. The Multiple Regression analysis revealed that obstacle height predicts head pitch angle magnitude in phase 2, pre-obstacle phase and post-obstacle phase in condition 3 (Appendix F).

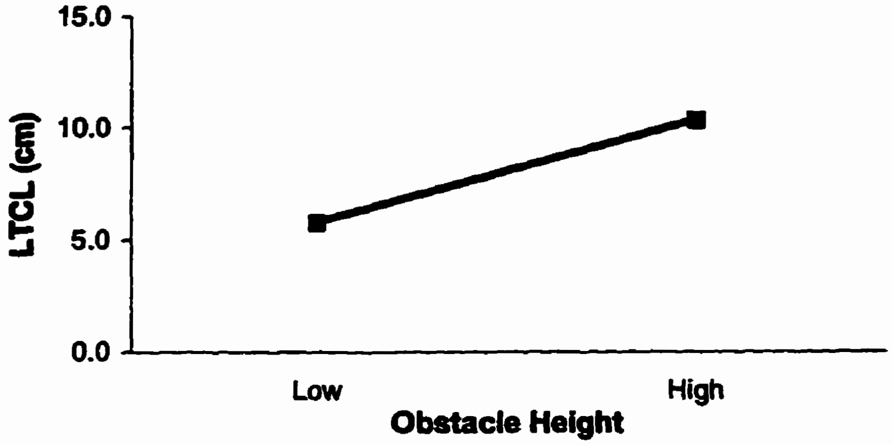

Figure 27. Main effect of obstacle height on leading toe clearance (LTCL).

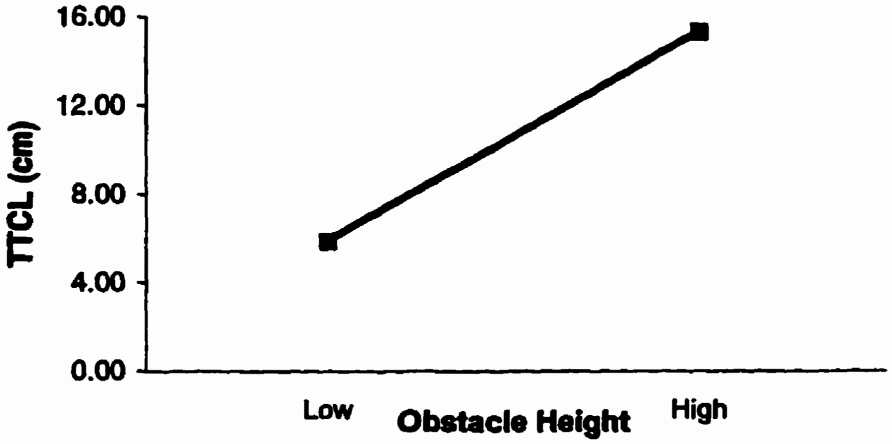

Figure 28. Main effect of obstacle height on trailing toe clearance (TTCL).

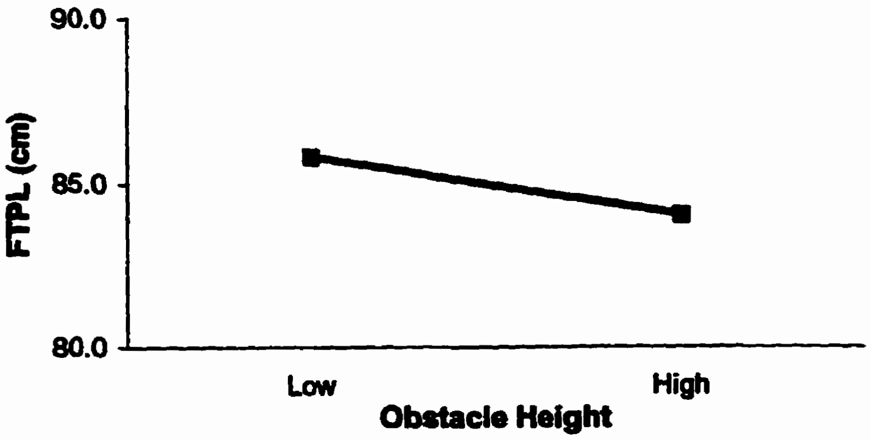

Figure 29. Main effect of obstacle height on foot placement before the obstacle (FTPL).

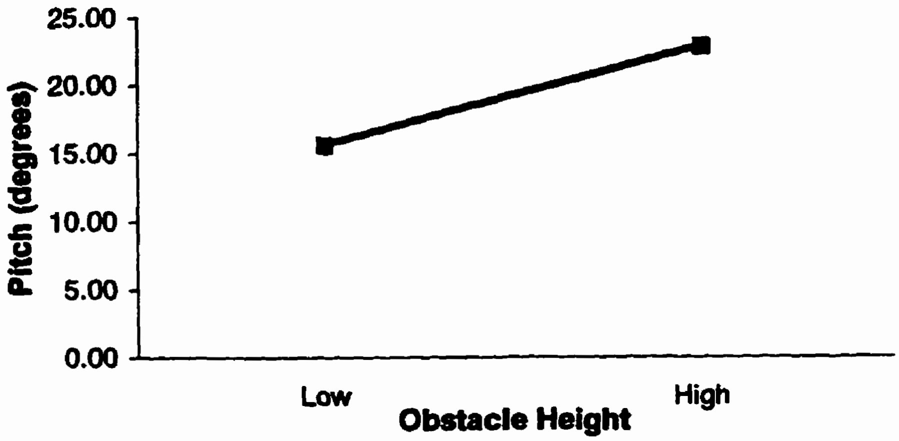

Figure 30. Main effect of obstacle height on head pitch angle magnitude in post-obstacle phase.

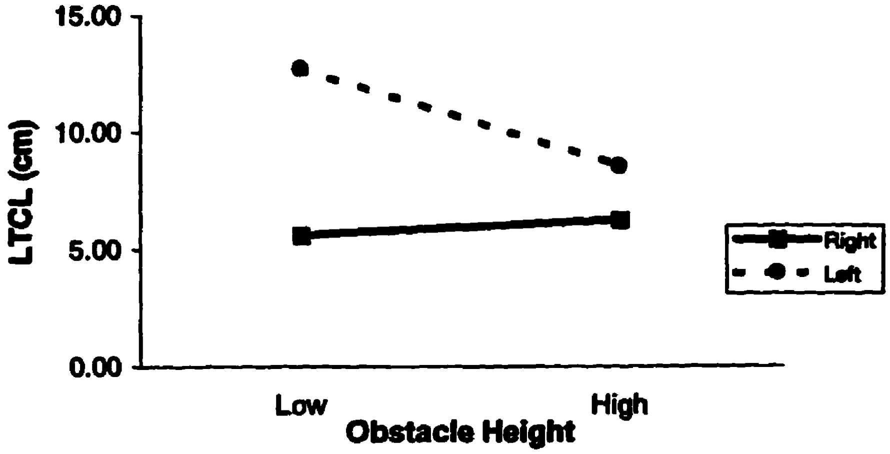

Figure 31. Interaction between leading leg preference and obstacle height on leading toe clearance (LTCL).

Vision: The statistical comparisons across conditions revealed a main effect of vision on head pitch angle magnitude in phase 1 ($F_{1,318}$= 4.04, p = 0.04, Figure 32); and in pre-obstacle phase ($F_{1,318}$= 4.59, p = 0.03, Figure 33).

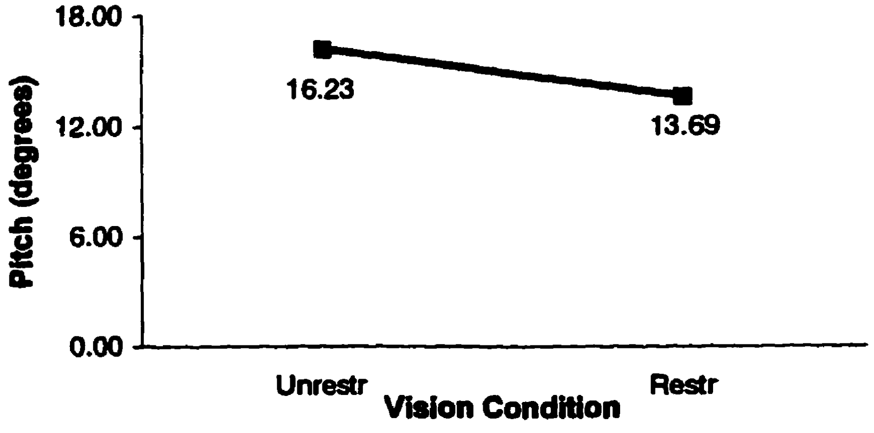

Figure 32. Main effect of vision on head pitch angle magnitude in phase 1.

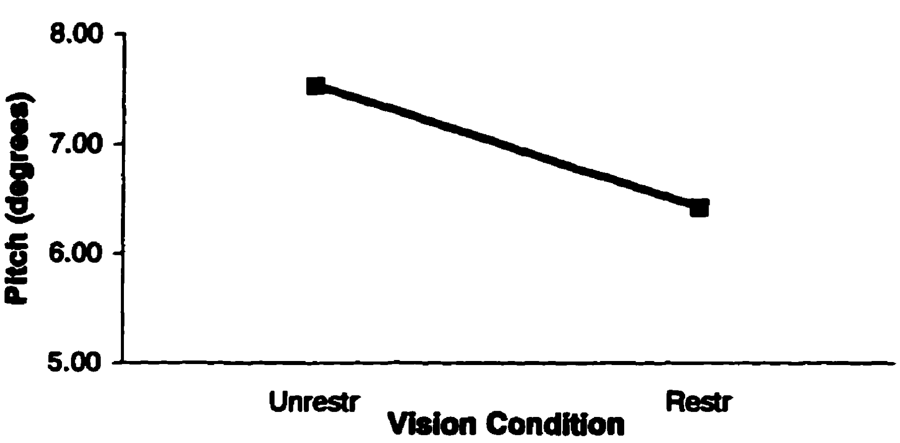

Figure 33. Main effect of vision on head pitch angle magnitude in pre-obstacle phase.

Subject Strategies: The statistical comparisons across conditions revealed a main effect of leading leg preference on leading toe clearance ($F_{1,413}$= 4.07, p = 0.04, Figure 34);on trailing toe clearance ($F_{1,381}$= 13.14, p = 0.0003, Figure 35); on foot placement before the obstacle ($F_{1,381}$= 12.01, p = 0.0006, Figure 36); and on head pitch angle magnitude in phase 2 ($F_{1,381}$= 13.14, p = 0.0003, Figure 37). Multiple regression analysis revealed that leading leg preference explains the variability of failure rates, leading toe clearance and foot placement before the obstacle in condition 2; leading toe clearance in condition 3 and 4 (Appendix E); and head pitch angle magnitude in phase 1 and condition 1 (Appendix F).

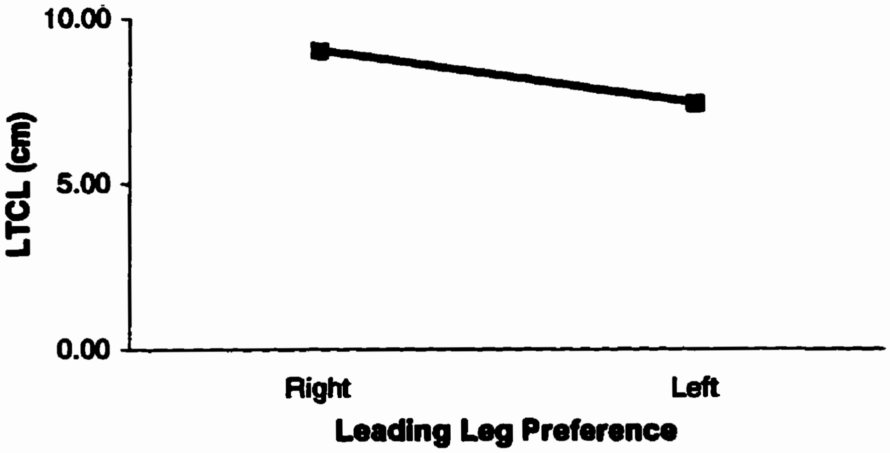

Figure 34. Main effect of leading leg preference on leading toe clearance (LTCL).

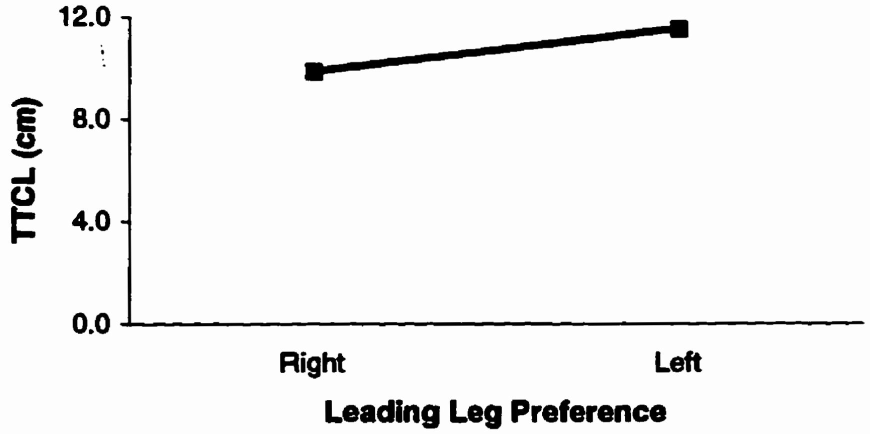

Figure 35. Main effect of leading leg preference on trailing toe clearance (TTCL).

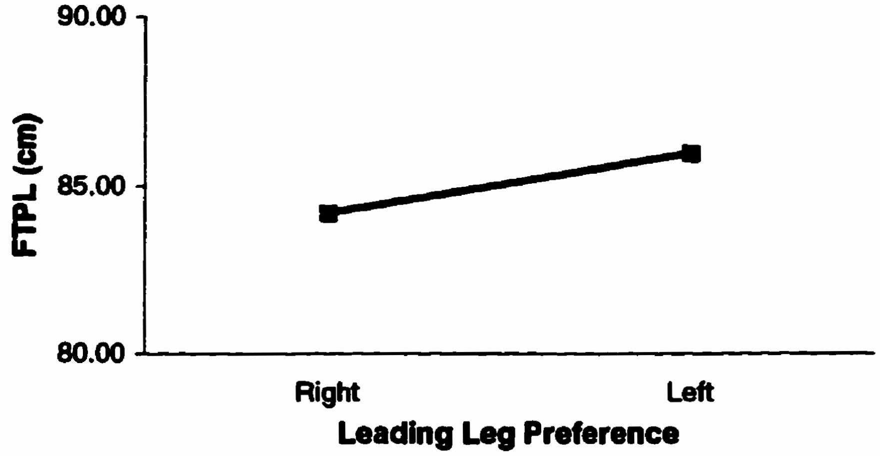

Figure 36. Main effect of leading leg preference on foot placement before the obstacle (FTPL).

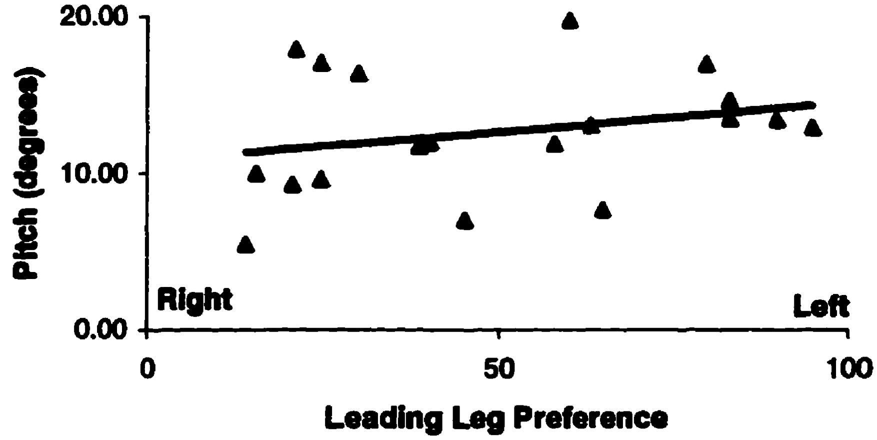

Figure 37. Main effect of leading leg preference on head pitch angle magnitude in phase 2.

The statistical comparisons across conditions revealed a main effect of leading foot placement before the obstacle on leading toe clearance ($F_{1,413}$= 7.59, p = 0.0006, Figure 38). According to the multiple regression analysis, foot placement before the obstacle predicts failure rates and leading toe clearance in condition 1, and leading toe clearance in condition 2 (Appendix E). The same statistical procedure revealed that leading toe clearance explains the variability of failure rates and foot placement before the obstacle in condition 2. Failure rates predicts trailing toe clearance and foot placement before the obstacle in condition 1; leading and trailing toe clearance in condition 2; trailing toe clearance in condition 4 (Appendix E); head pitch angle magnitude in phase 1 and condition 1; and in post-obstacle phase and condition 3 (Appendix F).

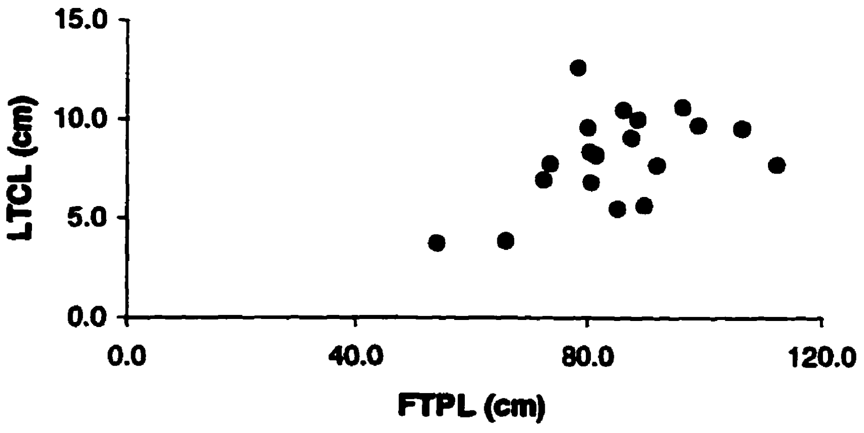

Figure 38. Main effect of leading foot placement before the obstacle (FTPL) on leading toe clearance (LTCL).

For head motion, the statistical comparison across condition revealed a main effect of head pitch angle magnitude in phases 1 and 2 on head pitch angle magnitude in pre-obstacle phase ($F_{1,318}$= 4.15, p = 0.04, Figure 39; $F_{1,318}$= 12.74, p = 0.0004, Figure 40); and on post-obstacle phase ($F_{1,318}$= 6.65, p = 0.01, Figure 41; $F_{1,318}$= 6.07, p = 0.01, Figure 42).

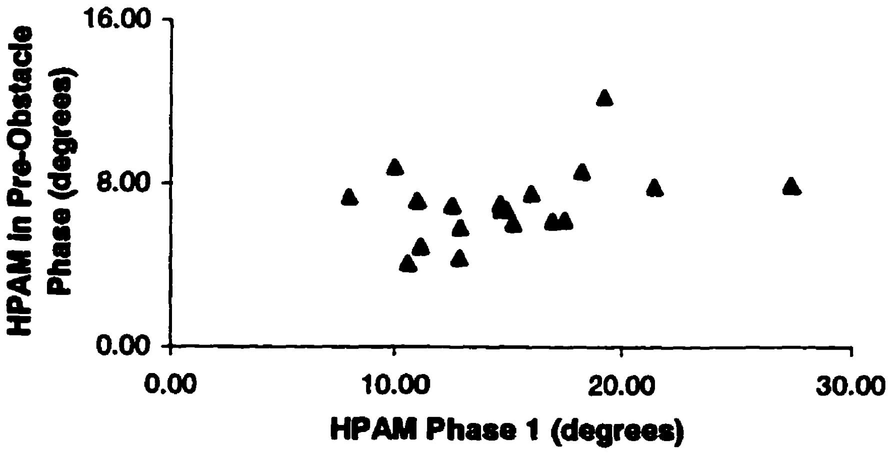

Figure 39. Main effect of head pitch angle magnitude (HPAM) in phase 1 on pre-obstacle phase.

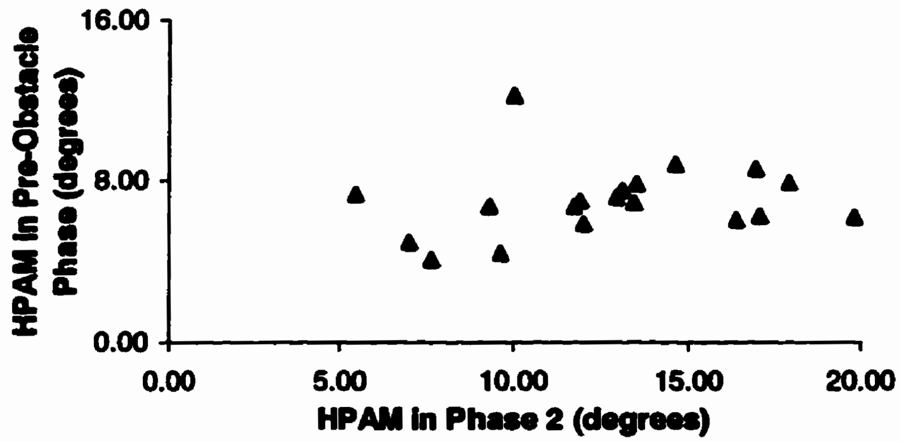

Figure 40. Main effect of head pitch angle magnitude (HPAM) in phase 2 on pre-obstacle phase.

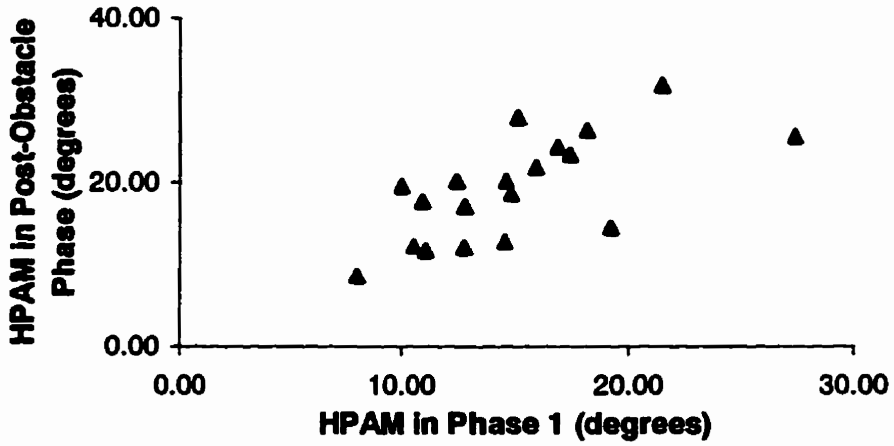

Figure 41. Main effect of head pitch angle magnitude (HPAM) in phase 1 on post-obstacle phase.

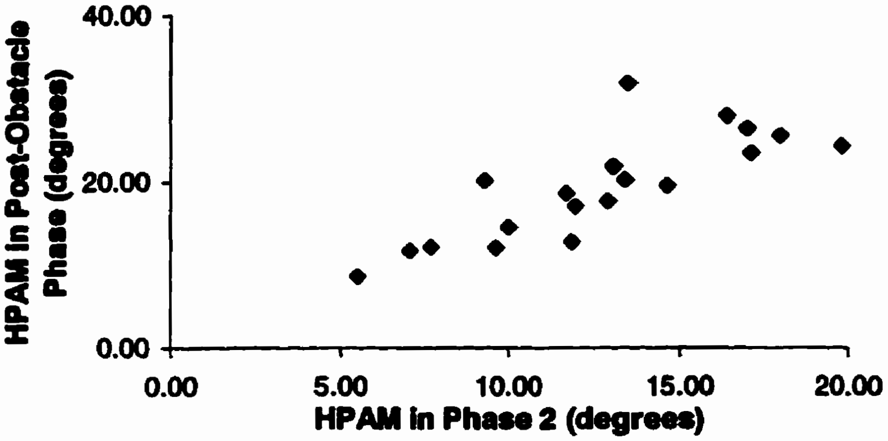

Figure 42. Main effect of head pitch angle magnitude (HPAM) in phase 2 on post-obstacle phase.

Exproprioceptive Information: The statistical comparison across condition revealed a main effect of leading toe clearance on trailing toe clearance ($F_{1,381}$= 27.46, p = 0.0001, Figure 43).

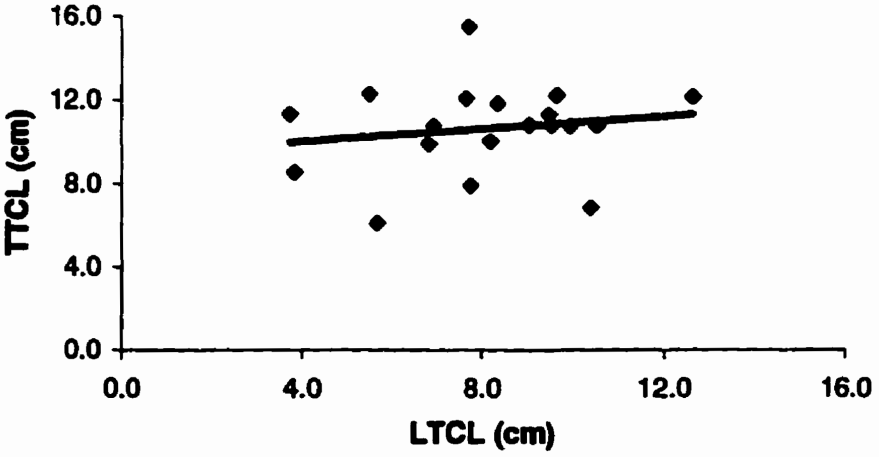

Figure 43. Main effect of leading toe clearance (LTCL) on trailing toe clearance (TTCL).

Discussion

Since 16 out of 20 participants in the present study also volunteered for Study # 1, there is a clear possibility of carry over effects from the first study, even though they were carried out more than 2 months apart. In this study, where a more challenging environment was faced by children, important findings showed up.

Growth and Development: Developmental variables, including chronological age and walking experience, reflect the effects of maturation and learning on sensory-motor transformations to achieve skilled locomotor behavior over obstacles. A more challenging experimental set up, decreasing the contrast between the obstacle and the ground was necessary to show maturation and learning effects. Chronological age affecting head motion before the obstacle revealed that younger children moved less their head to see the obstacle and the leading limb, and consequently moved also less after the obstacle than older children. Locking the neck is an adaptive strategy that decreases degrees of freedom of the system and facilitates motor control (Assaiante et al., 1993; Bernstein, 1940; Bronstein et al., 1996). Assaiante and Amblard (1993) observed the fact that when young children walked on a narrow surface they locked the trunk and neck segments. Gender also affected head motion prior to the obstacle revealing that sensory-motor transformations in boys mature earlier. Limb kinematic variables as leading and trailing toe clearance and foot placement before the obstacle were affected by anthropometric features, age and walking experience. This can be an indication of the different development rates of the system's components. Not only the physical growth rates are different across body segments, but also the rate of change can influence the internal representation of the body, which indirectly affects the movement pattern. Sutherland et al. (1988) reported that the upper part of the body represents a greater percentage of the total height in their younger subjects (1 to 3 years of age) with the equality between upper and lower body heights achieved by age 5. In addition, other systems are also developing in parallel at different rates and contributing to the behavioural manifestations in different ways (Thelen et al., 1994). A combination of maturation and environment exploration improves balance control and consequently sensory-motor transformations to achieve an efficient and economical limb motion over the obstacle. Gabbard (1992) demonstrated that from 5 to 11 years of age individuals show consistent improvements in integrating visual and kinesthetic information.

The results show that young children flexed the neck more than older children, revealing that young children acquired visual exteroceptive information in phase 2. It indicates that young children need to continually extract visual information, while older children can wait till they approach closer to the obstacle. Using the last stride to acquire exproprioceptive information to plan the modulation of limb trajectory reflects an adaptive strategy. However, another possible interpretation refers to necessary time to acquire exproprioceptive information. Older children maybe require less time to extract visual information and to modulate the effector system than young children.

Visual Information: Researchers (Pozzo et al., 1989; Pozzo et al., 1990) have used head movements to infer gaze control during locomotion. We recognise that eye movements confounds this issue. Nevertheless, reduction in VOR gain during locomotion allow us to use head movements to infer spatio-temporal acquisition of exteroceptive and expproprioceptive information. We focus our attention on pitch movements of the head since they directly impact on acquisition of visual information about the obstacle and the lower limbs. The partition of the head pitch motion in phases according to the strides before and after the obstacle permits the identification of when and where children extract exteroceptive and expproprioceptive information. A stereotypical profile revealed that in phase 1, head pitch motion was characterised by a small neck extension followed by a neck flexion and typically flexion in phase 2. In the pre-obstacle phase, head pitch motion was characterised by a small neck flexion, while large extension was observed at post-obstacle phase. It indicates that children extracts exteroceptive information one full stride prior to the obstacle.

By restricting vision of both leading and trailing limbs, the effects of expproprioceptive information were directly examined. The results indicated that lead and trail limb modulation are coupled in children as observed in Study 1. Leading toe clearance increased when vision was restricted. This result, even though not statistically significant, reveals that children were able to plan in advance the adaptive strategies by extracting visual exteroceptive information. This trend was confirmed by the reduced magnitude of head pitch angle in both phase 1 and pre-obstacle phase. In addition, it is also possible that holding the neck flexed in pre-obstacle phase, children manipulated their head movements to acquire some expproprioceptive information to guide the leading limb over the obstacle. However, holding the neck flexed in pre-obstacle phase was a selected strategy independent of age. When young adults were asked to wear goggles and step over the obstacle, vision condition did not influence the head pitch angle magnitude (Patla et al., 1993b).

One of the major findings of this study was limb and head modulations as a function of obstacle height. As obstacle height increased, an increase in leading toe clearance, trailing toe clearance and head pitch angle magnitude after the obstacle were observed. Foot was placed closer to high obstacle than to low obstacle. These results replicate some findings in Study # 1, and mirror the findings on healthy elderly adults and age-related maculopathy subjects found by Patla and colleagues (1996). Increasing leading toe clearance as obstacle height increases reflects the influence of the exteroceptive information on the modulation of the effector system. In healthy young and elderly adults, foot placement before the obstacle is not influenced by obstacle height. However, healthy elderly subjects consistently located their leading foot far away from the obstacle, and showed a larger toe clearance (Patla et al., 1996). The modulation of the trailing limb extremity according to the obstacle height indicates that exteroceptive information and kinesthetic input from the leading limb are used to fine tune trail limb trajectory. Adopting this strategy, children were revealing the time necessary to monitor and make on-line modifications to the leading limb trajectory over the obstacle. This strategy also implies that the trailing limb is not too close to the obstacle at toe-off and balance control is not compromised. Thus, exteroceptive and expproprioceptive information are used by children when stepping over obstacles.

Focusing on kinesthetic input, the results of the first study were replicated in the present study. Leading toe clearance positively influenced trailing toe clearance, which reveals that the kinesthetic input from the leading limb is useful to modulate on-line the trailing limb. In contrast, Patla et al. (1996) reported that a relatively independent control between leading and trailing limbs was observed for young adults.

Study # 3

Kinetic analyses of the swing limb during walking over obstacles in children

Introduction

In order to achieve a coordinated motor act, the central nervous system (CNS) uses an abstract, functionally specific equation of motion which is derived from Newtonian mechanics. The torques acting on limb joints are partitioned into several components: muscle moments and motion dependent torques (i.e., linear and angular accelerations and velocities for each segment). This computation generates a coordinated pattern of joint torques. According to Smith et al. (1991), the CNS deals separately with movement dynamics (forces and torques) and kinematics (direction, velocity, acceleration).

After analysing the adult pattern of walking, Bernstein (1940) applied dynamic calculations to understand the ontogenesis of locomotion. His studies showed that many components of the adult locomotor act were not observed in the locomotor pattern of children who had just started to walk independently. Among components that were absent were horizontal forces of the center of mass of the foot and shin at foot contact and the horizontal velocity of the thigh during the support phase. However, both horizontal acceleration curves of the leg as a whole during the swing phase and the reverse wave of the foot accompanied by the purely reactive-mechanical effect in the thigh at the beginning of the swing phase were present in the first day of independent walking. Nevertheless, Ulrich et al. (1994), examining the swing phase of infants held on a treadmill observed that muscle torque remained flexor throughout the swing phase. The pattern of locomotion observed by Bernstein (1940) was retained during the first year of walking, which he termed "*the innervationally primitive stage*". After this stage, improvements observed in structural elements of walking are not due to improvements in co-ordination and equilibrium. Instead they are related to the development of the CNS and the improved usage of proprioceptive information. "The whole inventory of dynamic waves develops very slowly, being complete by about the 5th year" (Bernstein, 1940, p. 189).

Thelen and colleagues (Schneider et al., 1990; Jensen et al., 1994; Ulrich et al., 1994) have been studying motor development under the umbrella of inverse dynamics. In their first study using this approach, Schneider et al. (1990) examined limb intersegmental dynamics from spontaneous kicks of varied intensity in order to explore how the neuromotor system of young infants controls a range of active and passive forces to produce a stereotypic, nonintentional movement. Six 3-month-old subjects were held in a supine position which allowed free movements of lower limbs. A movement of the lower limb, beginning from a extended position, moving through a single knee/hip flexion phase, and ending with a hip/knee extension phase was defined as a kick. The analyses of the 14 kicks revealed that in nonvigorous kicks, hip joint reversal was the result of an extensor torque due to gravity, opposed by the combined flexor effect of the muscle torque and the total motion-dependent torque. In more vigorous kicks, the motion-dependent hip flexor torque increased requiring an hip extensor torque to counter the motion dependent torque.

The muscle torques were adjusted to produce a net torque to reverse the kick motion of the linked segments. The authors concluded that because these kicks were spontaneous and without speed and accuracy constraints, they may be organized at a relatively lower level.

Jensen et al. (1994) tested spontaneous kicks of nine 3-month-old infants using the same procedure of Schneider et al. (1990) and adding to the supine position another two postures: angled and vertical. By manipulating posture they were able to assess the sensitivity of the infant motor system to changes in the gravitational context. Fifty kicks were analysed including 8 supine, 14 angled and 28 vertical motions. Their results showed that muscle torques required to drive hip flexion in the more upright postures were 4 to 10 times greater than in the supine position. In the vertical position, there was an increase in synchronous joint flexion, increased extension at the hip and knee and a reduction in hip range of motion. Subsequently, there were highly correlated hip and knee muscle torques in the vertical posture as opposed to supine or angled postures. This correlation implicates anatomical and energetic constraints in creating co-ordinated limb behavior out of non-specific muscle activations. Their data suggest that interjoint co-ordination may be an emergent property whose non-specific control parameters such as gravity shift the system into more tightly co-ordinated interjoint actions.

Ulrich et al. (1994) studied treadmill stepping in infants and adults using inverse dynamics with the purpose of comparing the patterns of active (muscle) and passive (gravity and motion-dependent) torques during the swing phase. The 8 young adult subjects walked on a treadmill at three speeds (slow, moderate and fast). The eight 7-month-old infant subjects were supported upright on a smaller treadmill at two speeds (slow and moderate or optimal). The trials analysed for adult subjects were 40 step cycles at slow and fast speed and 38 at moderate speed. For infants, the final analyses included 24 step cycles plus 13 swing phases at slow speed and 41 step cycles plus 4 swing phases at moderate speed. Their results indicated that for adults the muscle torques initiate and terminate the swing phase whereas the passive torques account for leg motion during most of the swing phase. However, infants showed that muscle torque remained flexor throughout the swing phase and joint reversals were due to the dominant passive gravitational torque. Based on the results of inverse dynamics analyses, the authors concluded that: a) adults seem to exploit and control the biodynamic properties of their limbs and the passive gravitational forces to enhance and maintain forward movement but used muscle torques to initiate and control joint reversals; and b) the infant motor system is susceptible to the influences of environmental constraints, but it is unable to fully exploit them. This means that the basic neural network is established early in human development but it is loosely organized.

In a previous study (Patla et al., 1996), we compared the relative contribution of hip hiking to toe clearance in young children, young and older subjects. The results showed that young children and older adults showed a higher contribution than young adults (over 30% compared to around 20% for young adults). Based on relatively small changes in the angular displacements of the hip, knee and ankle joint, we speculated that the larger contribution of hip hiking to toe clearance may reflect an inability to exploit the passive intersegmental dynamics to achieve swing limb flexion over obstacles.

Based on these studies, we set two goals for the third study. The first is to examine muscle moments of the swing limb trajectory of young children while stepping over obstacles of different features. The second is to analyse the influence of maturation and walking experience in the exploitation of the passive and active forces through the inverse dynamics technique during the swing phase.

Methods

Subjects: Fifteen children, ranging in age from two to six years, who stepped over the obstacles in Study 1 with the right leg, participated in the present experiment. The gender, chronological age, walking experience, hip height and body weight of each child were recorded and are presented in Table 5. Chronological age ranged from 26 to 70 months. Walking experience, defined as the number of months of independent walking, ranged from 13 to 58 months.

Table 5. Subject characteristics: gender, chronological age, walking experience, hip height and body weight.

Subject	Gender	Chronological Age (months)	Walking Experience (months)	Hip Height (cm)	Weight (kg)
C	F	36	24	47.3	17
D	M	60	47	57.1	16
E	F	46	35	50.1	17.3
G	M	45	34	48.8	15.9
H	F	56	43	50.3	18.6
I	F	31	14	39.2	13.2
J	F	36	26	43.2	16.4
K	M	60	50	52.2	21.4
L	M	43	31	44.1	15
M	F	41	30	43.6	16.1
N	M	69	54	62.5	25
O	M	54	37	53.4	18.3
Q	M	70	58	56.6	24.5
S	F	26	13	38	14.1
T	M	42	30	42.6	16.6

Procedures: The procedures, the data collection and obstacle features were the same as in Study # 1. For each trial the following kinematic measures were taken: relative hip, knee and ankle angles. For the kinetic data analysis, the joint moments at the hip, knee, and ankle during the swing phase were calculated using a standard inverse dynamics approach (Winter, 1991). Next, the contribution to the angular acceleration of the segment by the muscle moment, gravitational moment, and the moment due to motion dependent terms (linear and angular accelerations and velocity terms) were determined following the same procedure used by Patla and Prentice (1994). For each of the three joints the following general moment relationship was taken:

$$I \alpha = M_{MUS} + M_{MDT} + M_{GRA}$$

where:

I is the moment of inertia and α is the angular acceleration

M_{MUS} : is the moment derived from a standard inverse dynamic analysis and represents primarily the contribution of active muscle forces with some additional contribution from passive deformation of tissues surrounding the joint.

M_{MDT}: is the moment due to mechanical interactions between limb segments and contains angular and linear acceleration terms and angular velocity terms. The number of terms vary for each joint: hip and knee (7) and ankle (5). The detailed equations can be found in Schneider et al. (1990).

M_{GRA}: is the moment due to the gravitational force.

These joint moment profiles were taken between toe-off and when the toe is over the obstacle. The same statistical analyses used in studies #1 and #2 were carried out on only the muscle moment for each joint from toe-off and when the toe is over the obstacle.

Results

In Appendix G, means and standard deviations by subject for each kinetic variable are presented. The correlation matrices for each obstacle are presented in Appendix H.

Developmental Features: The statistical comparisons across obstacles revealed that chronological age marginally significantly affected ankle muscle moments ($F_{1,10} = 4.07$, p =

0.07, Figure 44); and knee muscle moments ($F_{1,8} = 4.17$, $p = 0.07$, Figure 45). Multiple Regression Analysis (Appendix H) revealed that chronological age explains ankle muscle moments at obstacles # 2 and 4; and ankle, knee and hip muscle moments at obstacle # 3. Walking experience predicts only ankle muscle moments at obstacle # 2.

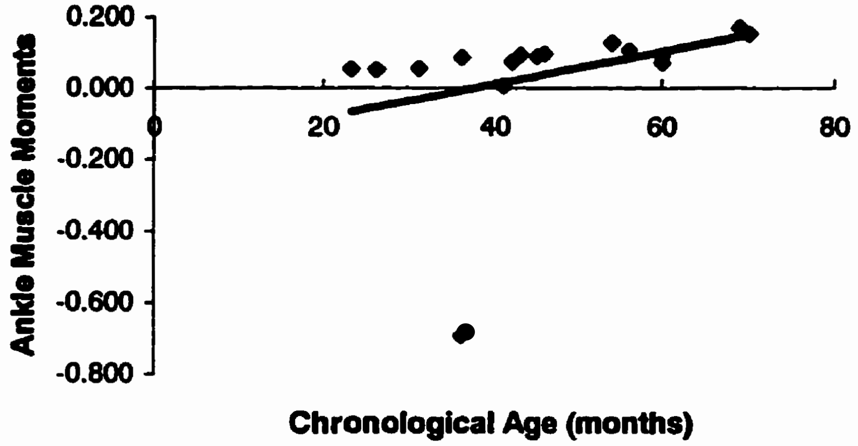

Figure 44. Ankle muscle moments according to chronological age.

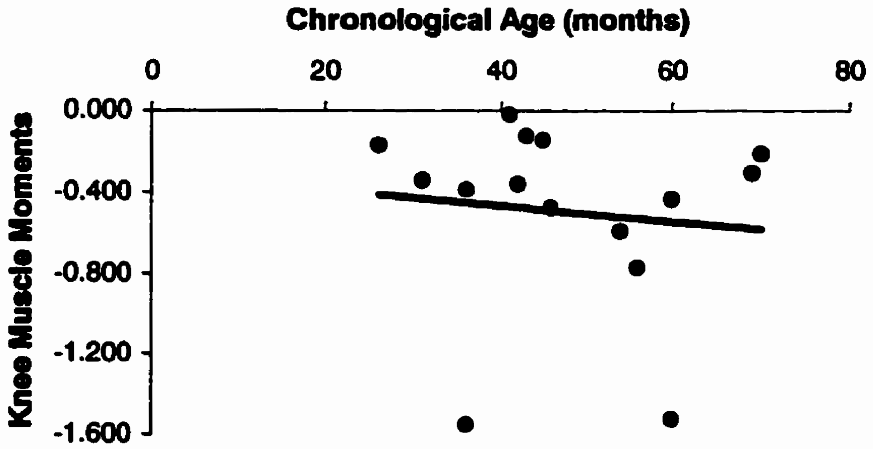

Figure 45. Knee muscle moments according to chronological age.

Anthropometric Variables: Body mass significantly affected only ankle muscle moments ($F_{1,10} = 8.29$, $p = 0.02$, Figure 46) as the statistical comparisons across obstacles revealed. Multiple Regression Analysis showed that body mass explains the variability of hip muscle moments at obstacle # 3. Hip height predicts hip muscle moments at obstacle # 1 and 2, while gender explains only hip muscle moments at obstacle # 1 (Appendix H).

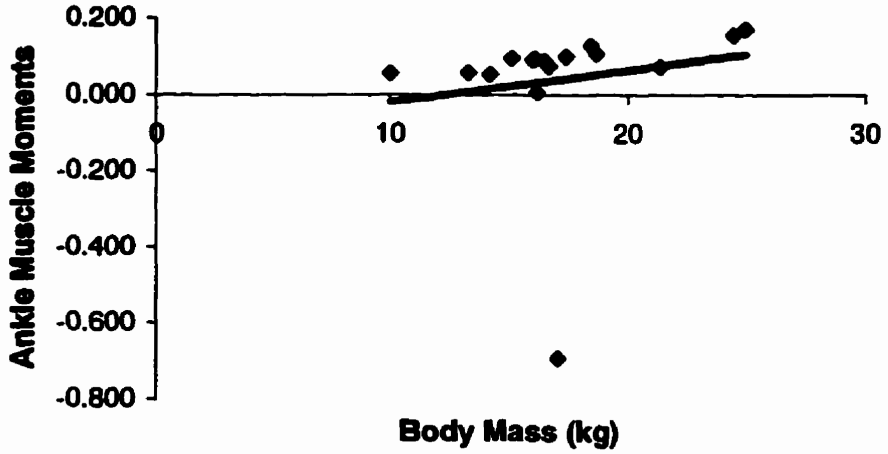

Figure 46. Main effect of body mass on ankle muscle moments.

Obstacle Features: The statistical comparisons across obstacle revealed a main effect of obstacle on knee muscle moments ($F_{1,102} = 4.46$, $p = 0.04$, Figure 47); obstacle height on hip muscle moments ($F_{1,102} = 4.72$, $p = 0.03$, Figure 48); and an interaction of obstacle height and width on ankle muscle moments ($F_{1,102} = 16.71$, $p = 0.0001$, Figure 49). Multiple Regression Analysis (Appendix H) revealed that obstacle height explains variability of hip muscle moment at obstacle # 1; and ankle muscle moment at obstacle # 2.

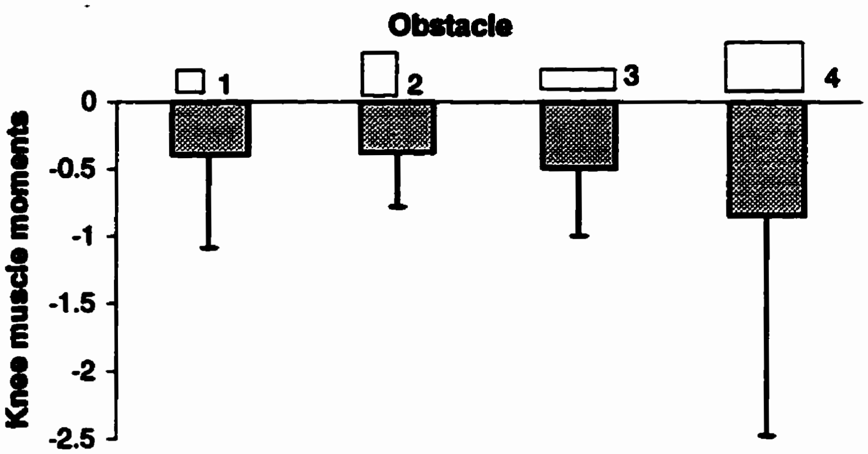

Figure 47: Main effect of obstacle on knee muscle moments.

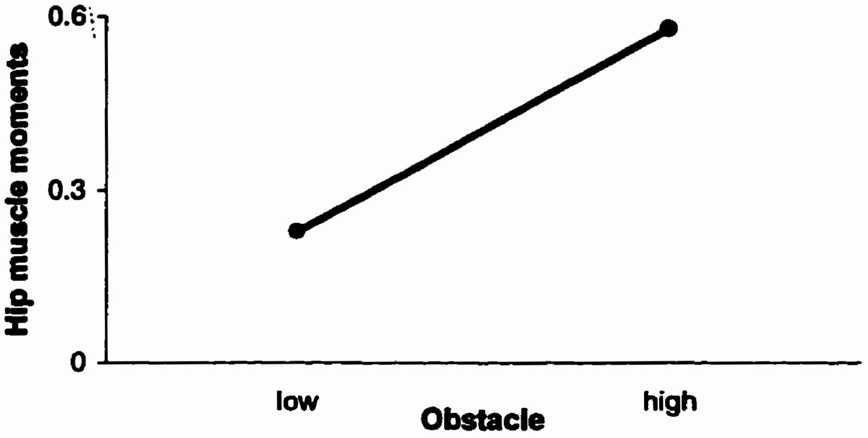

Figure 48. Main effect of obstacle height on hip muscle moments.

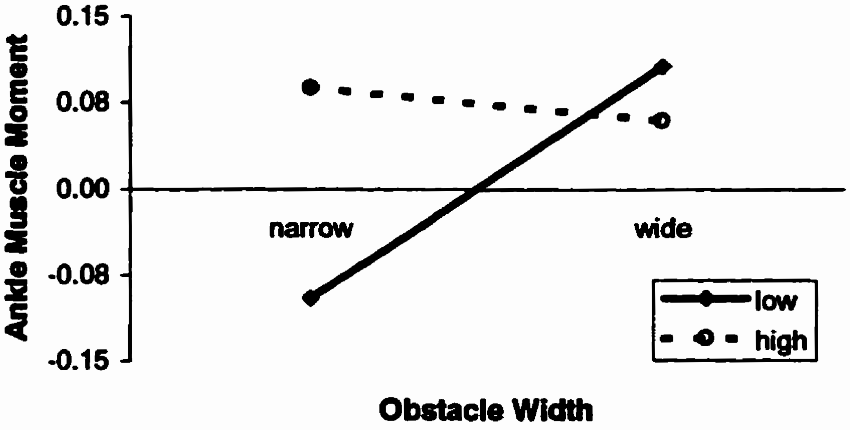

Figure 49. Interaction between obstacle height and width on ankle muscle moments.

Subject Strategies: Statistical comparisons across obstacles revealed main effects of knee muscle moments ($F_{1,102}$ = 14.78, p = 0.0002, Figure 50), and hip muscle moments ($F_{1,102}$ = 49.78, p = 0.0001, Figure 51) on ankle muscle moments; and an interaction between knee and hip muscle moments on ankle muscle moments ($F_{1,102}$ = 4.37, p = 0.04, Figure 52). Multiple Regression Analysis revealed that ankle muscle moments predicts hip muscle moments in all obstacles and knee muscle moments at obstacle # 3 (Appendix H). Related to knee muscle moments, statistical comparisons across obstacles revealed main effects of ankle muscle moment ($F_{1,102}$ = 7.88, p = 0.006, Figure 50) and hip muscle moment ($F_{1,102}$ = 292.44, p = 0.0001, Figure 53) on knee muscle moments. Multiple Regression Analysis of each obstacle revealed that knee muscle moments explains the variability of ankle and hip muscle moments at obstacle # 3 and hip muscle moments at obstacle # 4 (Appendix H). Statistical comparisons across obstacles also revealed that hip muscle moments were significantly affected by ankle muscle moment ($F_{1,102}$ = 63.78, p = 0.0001, Figure 51), and knee muscle moment ($F_{1,102}$ = 146.58, p = 0.0001, Figure 53). Multiple Regression Analysis (Appendix H) revealed that hip muscle moments predicts ankle muscle moments at all obstacles, and knee muscle moments at obstacles # 3 and 4.

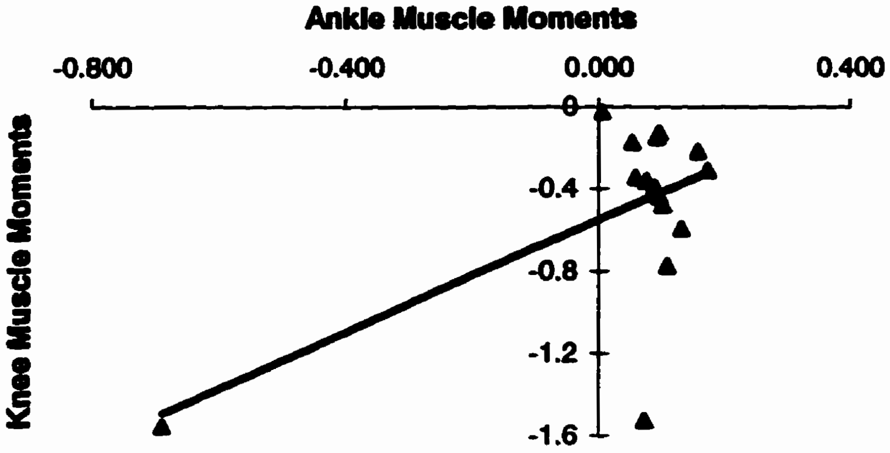

Figure 50. Main effect of knee muscle moments on ankle muscle moments.

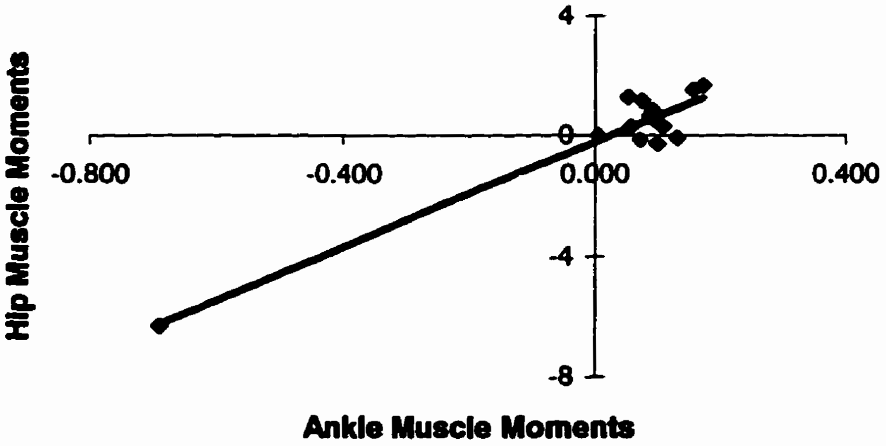

Figure 51. Main effect of hip muscle moments on ankle muscle moments.

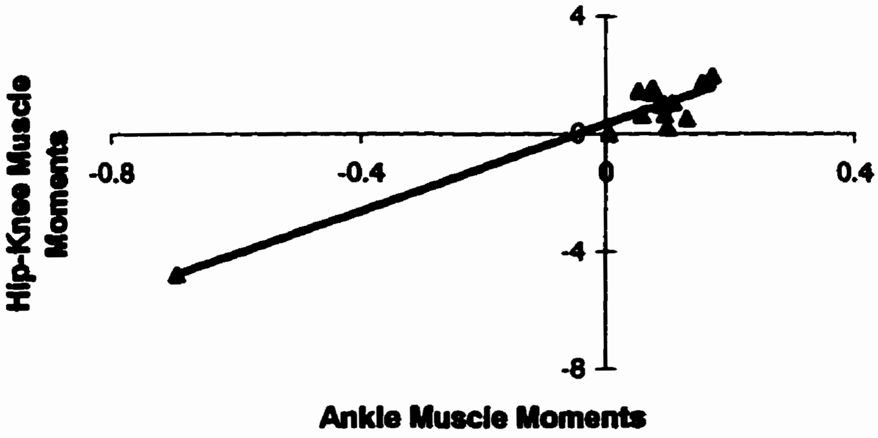

Figure 52. Interaction between hip and knee muscle moments on ankle muscle moments.

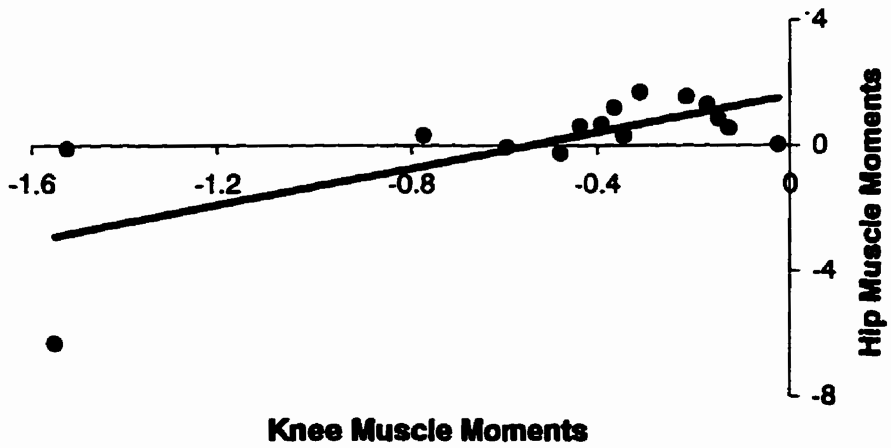

Figure 53. Main effect of hip muscle moments on knee muscle moments.

Discussion

Muscle moment, as derived by calculations of inverse dynamics, reflects active muscle contraction and viscoelastic properties of soft tissues. The nervous system directly controls only muscle moment on limb movement. Swing limb flexion over the obstacle is achieved by flexing the hip, knee and ankle joint (Patla et al., 1993a) The active contribution of the muscles around the hip and ankle joints are not modulated as a function of obstacle height (Patla et al., 1994; Patla et al., 1996). The nervous system is able to simplify the control of the limb elevation at the obstacle through the exploitation of the passive interactions between segments in healthy young and elderly adults.

Growth and Development: Results of this study showed two developmental trends. Ankle muscle activation increased with age while a decreased muscle activation was observed around the knee joint with age. In healthy young and elderly adults, hip and ankle flexion from the toe-off to when the toe is over the obstacle is a result of the passive intersegmental dynamics. The central nervous system actively controls adult knee muscles to step over obstacles (Patla et al., 1994; Patla et al., 1996). Children, on the other way, are not able to exploit the passive forces. Since there is a positive correlation between body mass and chronological age (Sutherland et al., 1988), increasing ankle muscle moment can be attributed to a misjudgment of obstacle features. Decreasing knee flexion with age indicates that the central nervous system is modulating ankle and hip joints to raise the limb and clear the obstacle. These results confirm Bernstein (1940) observations related to the maturation of the CNS in modulating the effector system according to the proprioceptive information. This sensory-motor transformation should be completed at age of 5 (1940). A deeper analysis of the moments due to gravity and mechanical interactions between limb segments could enhance the developmental effects; as well as a eletromyographic analysis during the swing phase in children while stepping over obstacles could provide a wider picture of the muscle activation.

Sensory Information: The major finding in this study refers to different effects of obstacle features on muscle activation around the three joints. Hip muscle moments were affected by obstacle height; knee muscle moments were affected by a combination of obstacle features; and ankle moments were affected by obstacle height and width. Unlike adults, which on flat surfaces apply muscle torques only to initiate and terminate the swing phase (Ulrich et al., 1994) and over obstacles activate muscles around the knee joint (Patla et al., 1994) children activate muscles around all three joints. This strategy is not efficient, indicating an inability to exploit intersegmental dynamics. However, respecting the proximal to distal development principle, the nervous system is directly controlling the hip as a proximal joint and knee and ankle to raise the foot to ensure a large safety margin over the obstacle. Even though this strategy is not efficient, it is effective. Muscle activation around the hip joint according to obstacle height confirms kinematic results of hip elevation in Study 1 and in our previous study (Patla et al., 1996). A more challenging obstacle (# 4) required a bigger knee muscle activation than other obstacles. The interaction between obstacle height and width for ankle muscle moment, as well as the leading toe clearance values reported in Study # 1, indicate that children were actively flexing the ankle joint to clear the obstacle.

Intersegmental Dynamics: Main effects of hip and knee muscle moments on ankle muscle moments were detected. As hip and knee muscle moments increased, the muscle moment around the ankle joint also increased. These results indicate that the muscle activity around each joint is closely controlled by the nervous system. It also revealed that all three joints are coupled, which confirms Ulrich et al. (1994) data. Limb joints coupled during the swing phase reflects that adaptations of the effector system to provide a simple and efficient control are developing, as observed in other studies (Jensen et al., 1994; Ulrich et al., 1994).

Conclusion

The aim of this thesis was to investigate how sensory inputs are integrated and used to guide motor action as a child matures. Children improved their sensory-motor transformation; however, compared with adults, their strategies to step over obstacles revealed immature usage of exteroceptive, expproprioceptive, and kinesthetic information, as well, they were unable to exploit the intersegmental dynamics. Affordances for locomotion over uneven terrain were present and children in this age range successfully stepped over the obstacle. With a less challenging experimental set up as in Study 1, children showed only a few differences according to age and anthropometric features, because subjects may choose among several or many possible responses. However, in Study 2, with a more challenging environment, effects of development, understood here as maturation plus experience, were observed.

As Thelen and Smith (1994) reported in treadmill stepping, the development and refinement of the sensory-motor integration does not obey a pre-determined sequence of behavioral milestones, but rather emerges from the convergence of different rates as each component evolves. In stepping over obstacles, the children's behaviour revealed several effects of chronological age and walking experience, as well as larger variability within subjects in each dependent measure. Differences across children in the behavioral adaptations to environmental demands revealed some effects of exposure to a complex environment. Older and more experienced children revealed better sensory-motor transformation than younger children. This is due to different rates that each subsystem develops in time as well as environment and task changes. Even if these changes were small they can lead to large reorganizations in the motor behavior (Thelen and Smith, 1994).

The results from Study 2 revealed the strategies utilised by younger and older kids to extract exteroceptive and expropriocepti̇ve information. Blocking the neck when wearing a collar showed that young children reduce the degrees of freedom of the system to decrease the demands over the system. It indicates that the control system is immature not only in integrating sensory information but also in modulating the lower limbs to step over the obstacle.

In all three studies, it was observed that obstacle features affect limb modulation. The perception of the obstacle features produce effects on subject strategies, identified kinematically. When joint kinetics were analyzed in Study 3, obstacle features also affected the use of muscles around all three joints of the lower limb, indicating an inability to exploit intersegmental dynamics. However, it is necessary to analyze the motion dependent component joint torque from the inverse dynamics to verify moments due to mechanical interactions.

Returning to the jigsaw puzzle metaphor, several key components of the model were tested and the assumptions made were verified. One assumption was that the pieces representing a child were neither sculpted nor integrated to generate successful and efficient strategies to step over obstacles. This was confirmed by the developmental trend to acquire exteroceptive information when children were exposed to a more challenging environment, as well as by their inability to exploit intersegmental dynamics to flex the limb over the obstacle efficiently. The assumption that balance was also achieved through the sculpting and integration of the components in the puzzle needs further and more specific investigation. However, postural adjustments and strategies, such as asking for assistance in young children were observed.

The major assumption of the puzzle metaphor was related to the development process. We based our theoretical framework on Karmiloff-Smith's (1992) approach of development, which emphasizes an integration of some built-in knowledge and experience. After the data collection, analyses and interpretations of the results we have evidence to support this approach. Motor development is dynamic and continuously occurring by exposing organism to information about itself, the task and the environment. The process to build the knowledge about obstacle avoidance strategies requires among others, sensory exploration, affordance learning, continuous upgrading of the components of the system according to physical growth, and exposure to complex environments, which challenges the child's development.

Future research, such as studying children under a longitudinal approach, would allow for an investigation of the parameters underlying behavioral changes in obstacle avoidance, particularly to understand the dynamics of these changes. For example how postural and balance control develop and interfere with obstacle avoidance strategies in children within a larger age range and sample can be explored using a less sophisticated experimental set up. Intersegmental dynamics analysis of both limbs in a more complex environment involving manipulation of room luminance would be beneficial. Changes in motor behavioral can be explained not only by neural and contextual contributions but also through biomechanical factors. The intention is also to apply mechanical perturbations during gait in order to document recovery.

The intention is to conduct a larger research project to investigate changes during the development in order to further refine the puzzle metaphor. Further research could provide evidence to include more pieces in the puzzle representing anthropometric variables and leg preference. Ultimately the goal is to determine the intrinsic mechanisms and principles underlying improvements in sensory-motor transformations during the development process.

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Appendix A

Samples of Statistical Analyses

Multiple Regression

```
                          11:03 Tuesday, April 23, 1996

      Forward Selection Procedure for Dependent Variable LTCL

Step 1  Variable OBST Entered    R-square = 0.08435258  C(p) =  8.98602870

            DF      Sum of Squares    Mean Square       F  Prob>F

Regression     1       1278.46663930  1278.46663930    35.93  0.0001
Error       390     13877.75737473    35.58399327
Total       391     15156.22401403

            Parameter      Standard       Type II
Variable        Estimate         Error  Sum of Squares        F   Prob>F

INTERCEP     14.13727667    0.69972868  14525.35823300    408.20  0.0001
OBST         -1.30052801    0.21697133  1278.46663930    35.93  0.0001

Bounds on condition number:         1,          1
------------------------------------------------------------------------

Step 2  Variable WALKAGE Entered  R-square = 0.08760399  C(p) =  9.57635409

            DF      Sum of Squares    Mean Square       F  Prob>F

Regression     2       1327.74575938    663.87287969     18.67  0.0001
Error       389     13828.47825465    35.54878729
Total       391     15156.22401403

            Parameter      Standard       Type II
Variable        Estimate         Error  Sum of Squares        F   Prob>F

INTERCEP     13.28819002    1.00459478   6219.77415311    174.96  0.0001
OBST         -1.31749030    0.21734198   1306.26837371    36.75  0.0001
WALKAGE      0.02742959    0.02329701    49.27912008     1.39  0.2398

Bounds on condition number:  1.004413,   4.017653
------------------------------------------------------------------------

Step 3  Variable HIPHT Entered    R-square = 0.10568743  C(p) =  3.73614235

            DF      Sum of Squares    Mean Square       F  Prob>F

Regression     3       1601.82229734    533.94076578     15.28  0.0001
Error       388     13554.40171669    34.93402504
Total       391     15156.22401403

            Parameter      Standard       Type II
```

```
Variable      Estimate         Error  Sum of Squares       F  Prob>F

INTERCEP    21.19924829    2.99480790   1750.45765192    50.11  0.0001
OBST        -1.30248706    0.21552106   1275.89827846    36.52  0.0001
WALKAGE      0.14081431    0.04660487    318.91850436     9.13  0.0027
HIPHT       -0.24363800    0.08698280    274.07653796     7.85  0.0053

Bounds on condition number:    4.092267,     27.56267
--------------------------------------------------------------------


Step 4   Variable AGE Entered       R-square = 0.10831750   C(p) =  4.59585172

              DF       Sum of Squares     Mean Square        F  Prob>F

Regression     4        1641.68434675    410.42108669    11.75  0.0001
Error        387       13514.53966729     34.92129113
Total        391       15156.22401403

              Parameter      Standard       Type II
Variable       Estimate         Error  Sum of Squares       F  Prob>F

INTERCEP    23.14155385    3.50293618   1524.09092299    43.64  0.0001
OBST        -1.29021285    0.21578781   1248.41569579    35.75  0.0001
WALKAGE      0.05955323    0.08919710     15.56680123     0.45  0.5047
AGE          0.12872368    0.12048244     39.86204940     1.14  0.2860
HIPHT       -0.35248339    0.13394826    241.82068146     6.92  0.0088

Bounds on condition number:    31.07471,     227.115
--------------------------------------------------------------------

Step 5   Variable GENDER Entered    R-square = 0.10969183   C(p) =  6.00000000

              DF       Sum of Squares     Mean Square        F  Prob>F

Regression     5        1662.51401068    332.50280214     9.51  0.0001
Error        386       13493.71000335     34.95779794
Total        391       15156.22401403

              Parameter      Standard       Type II
Variable       Estimate         Error  Sum of Squares       F  Prob>F

INTERCEP    24.19439462    3.76081208   1446.80606413    41.39  0.0001
OBST        -1.29091888    0.21590251   1249.75996817    35.75  0.0001
WALKAGE      0.06012307    0.08924677     15.86504823     0.45  0.5009
GENDER      -0.51396531    0.66583206     20.82966394     0.60  0.4406
AGE          0.12007505    0.12106497     34.38845373     0.98  0.3219
HIPHT       -0.35134730    0.13402634    240.23539004     6.87  0.0091

Bounds on condition number:    31.34316,     291.285
--------------------------------------------------------------------
```

```
No other variable met the 0.5000 significance level for entry into the model.

   Summary of Forward Selection Procedure for Dependent Variable LTCL

      Variable  Number  Partial   Model
 Step  Entered    In     R**2     R**2      C(p)        F  Prob>F

   1  OBST       1  0.0844  0.0844   8.9860   35.9281  0.0001
   2  WALKAGE      2  0.0033  0.0876   9.5764    1.3862  0.2398
   3  HIPHT      3  0.0181   0.1057   3.7361    7.8455  0.0053
   4  AGE       4  0.0026   0.1083   4.5959   1.1415  0.2860
   5  GENDER      5  0.0014  0.1097   6.0000    0.5959  0.4406
```

Backward Elimination Procedure for Dependent Variable LTCL

```
Step 0  All Variables Entered   R-square = 0.10969183  C(p) =  6.00000000

            DF      Sum of Squares     Mean Square        F  Prob>F

Regression    5       1662.51401068   332.50280214     9.51  0.0001
Error       386     13493.71000335   34.95779794
Total       391     15156.22401403

           Parameter     Standard        Type II
Variable        Estimate          Error  Sum of Squares        F  Prob>F

INTERCEP    24.19439462    3.76081208   1446.80606413     41.39  0.0001
OBST         -1.29091888    0.21590251   1249.75996817    35.75  0.0001
WALKAGE       0.06012307    0.08924677    15.86504823     0.45  0.5009
GENDER       -0.51396531    0.66583206    20.82966394     0.60  0.4406
AGE           0.12007505    0.12106497    34.38845373     0.98  0.3219
HIPHT        -0.35134730    0.13402634   240.23539004     6.87  0.0091

Bounds on condition number:   31.34316,      291.285
---------------------------------------------------------------------

Step 1  Variable WALKAGE Removed   R-square = 0.10864507  C(p) =  4.45383431

            DF      Sum of Squares     Mean Square        F  Prob>F

Regression    4       1646.64896245   411.66224061    11.79  0.0001
Error       387     13509.57505158   34.90846267
Total       391     15156.22401403

           Parameter     Standard        Type II
Variable        Estimate          Error  Sum of Squares        F  Prob>F
```

```
INTERCEP    24.49271501    3.73201388   1503.55071338     43.07  0.0001
OBST        -1.28345760    0.21546603   1238.61442760     35.48  0.0001
GENDER      -0.51025501    0.66533930     20.53141693      0.59  0.4436
AGE          0.18938141    0.06377305    307.84422256      8.82  0.0032
HIPHT       -0.38330965    0.12525918    326.89713738      9.36  0.0024

Bounds on condition number:    8.709506,      77.659
------------------------------------------------------------------------

Step 2   Variable GENDER Removed    R-square = 0.10729041   C(p) =  3.04115440

              DF        Sum of Squares      Mean Square         F   Prob>F

Regression     3        1626.11754552     542.03918184      15.54   0.0001
Error        388       13530.10646851      34.87140842
Total        391       15156.22401403

              Parameter        Standard          Type II
Variable       Estimate           Error   Sum of Squares        F   Prob>F

INTERCEP    23.44459589    3.47092415   1590.98008562     45.62  0.0001
OBST        -1.28282682    0.21535008   1237.41528404     35.49  0.0001
AGE          0.19731600    0.06289480    343.21375254      9.84  0.0018
HIPHT       -0.38413685    0.12518804    328.33391869      9.42  0.0023

Bounds on condition number:    8.491843,      53.93207
------------------------------------------------------------------------

All variables left in the model are significant at the 0.1000 level.

  Summary of Backward Elimination Procedure for Dependent Variable LTCL

        Variable   Number   Partial    Model
Step    Removed        In      R**2     R**2       C(p)          F   Prob>F

  1     WALKAGE         4    0.0010   0.1086     4.4538     0.4538   0.5009
  2     GENDER          3    0.0014   0.1073     3.0412     0.5882   0.4436
```

Stepwise Procedure for Dependent Variable LTCL

```
Step 1   Variable OBST Entered       R-square = 0.08435258   C(p) =  8.98602870

              DF        Sum of Squares      Mean Square         F   Prob>F

Regression     1        1278.46663930    1278.46663930      35.93   0.0001
Error        390       13877.75737473      35.58399327
Total        391       15156.22401403

              Parameter        Standard          Type II
```

```
Variable      Estimate        Error  Sum of Squares        F  Prob>F

INTERCEP    14.13727667    0.69972868  14525.35823300    408.20  0.0001
OBST        -1.30052801   0.21697133   1278.46663930    35.93  0.0001

Bounds on condition number:          1,          1
------------------------------------------------------------------------

All variables left in the model are significant at the 0.1500 level.
No other variable met the 0.1500 significance level for entry into the model.

       Summary of Stepwise Procedure for Dependent Variable LTCL

      Variable       Number  Partial   Model
Step  Entered Removed    In     R**2    R**2     C(p)        F  Prob>F

   1  OBST                1   0.0844  0.0844   8.9860  35.9281  0.0001
```

GLM procedure - LTCL

```
                    13:07 Saturday, June 22, 1996

              General Linear Models Procedure
                 Class Level Information

        Class   Levels   Values

        SUBJ       19    0 1 2 3 4 5 6 7 8 9 K M N O P Q S T Z


            Number of observations in data set = 327


NOTE: Due to missing values, only 306 observations can be used in this analysis.


              General Linear Models Procedure

Dependent Variable: LTCL
                         Sum of          Mean
Source          DF        Squares        Square   F Value    Pr > F

Model           27    5611.3701167    207.8285228    14.53    0.0001

Error          278    3977.5133996    14.3076022

Corrected Total     305    9588.8835163

          R-Square        C.V.      Root MSE        LTCL Mean

          0.585195      33.17865    3.7825391        11.400523


Source          DF      Type I SS    Mean Square   F Value    Pr > F

MASS             1     440.9230028    440.9230028    30.82    0.0001
HIPHT            1     990.4024624    990.4024624    69.22    0.0001
WALKAGE              1     191.3983545    191.3983545    13.38    0.0003
AGE             1      0.0335826      0.0335826     0.00    0.9614
FAIL            1     141.0956207    141.0956207     9.86    0.0019
MASS*HIPHT           1     205.5090468    205.5090468    14.36    0.0002
WALKAGE*AGE             1     111.1028155    111.1028155     7.77    0.0057
SUBJ            11     2968.3400904    269.8490991    18.86    0.0001
OBSTHT              1      37.4670063     37.4670063     2.62    0.1067
OBSTWD               1      28.4393617     28.4393617     1.99    0.1597
LEG             1      78.6375506     78.6375506     5.50    0.0198
HIPDIF           1     221.4332961    221.4332961    15.48    0.0001
FAIL*OBST            1       2.8626480      2.8626480     0.20    0.6550
```

```
OBSTHT*LEG          1    31.3019682    31.3019682    2.19   0.1402
OBSTHT*HIPDIF         1    94.4513346    94.4513346    6.60   0.0107
LEG*HIPDIF          1    45.4182148    45.4182148    3.17   0.0759
OBST            1    22.5537607    22.5537607    1.58   0.2103

Source          DF    Type III SS    Mean Square   F Value    Pr > F

MASS             0     0.0000000       .          .    .
HIPHT            0     0.0000000       .          .    .
WALKAGE            0     0.0000000       .          .    .
AGE              0    0.0000000       .          .    .
FAIL             0    0.0000000       .          .    .
MASS*HIPHT          0     0.0000000       .          .    .
WALKAGE*AGE          0     0.0000000       .          .    .
SUBJ            11    2594.6400757    235.8763705   16.49   0.0001
OBSTHT            1     1.8179633     1.8179633    0.13   0.7218
OBSTWD            1     33.7529321     33.7529321    2.36   0.1257
LEG             1     0.0069717     0.0069717    0.00   0.9824
HIPDIF            1    302.1016477   302.1016477   21.11   0.0001
FAIL*OBST           1     0.0415654     0.0415654    0.00   0.9571
OBSTHT*LEG          1     3.5947222     3.5947222    0.25   0.6166
OBSTHT*HIPDIF         1    59.0710612    59.0710612    4.13   0.0431
LEG*HIPDIF          1    46.0630196    46.0630196    3.22   0.0739
OBST            1    22.5537607    22.5537607    1.58   0.2103


                    General Linear Models Procedure

Dependent Variable: LTCL

Tests of Hypotheses using the Type I MS for SUBJ as an error term

Source          DF     Type I SS    Mean Square   F Value    Pr > F

HIPHT            1   990.40246238   990.40246238    3.67    0.0817

Tests of Hypotheses using the Type I MS for SUBJ as an error term

Source          DF     Type I SS    Mean Square   F Value    Pr > F

WALKAGE           1   191.39835448   191.39835448    0.71    0.4176

Tests of Hypotheses using the Type I MS for SUBJ as an error term

Source          DF     Type I SS    Mean Square   F Value    Pr > F

AGE              1    0.03358264    0.03358264    0.00    0.9913

Tests of Hypotheses using the Type I MS for SUBJ as an error term

Source          DF     Type I SS    Mean Square   F Value    Pr > F
```

```
MASS                1   440.92300279   440.92300279    1.63    0.2275

Tests of Hypotheses using the Type I MS for SUBJ as an error term

Source             DF      Type I SS    Mean Square   F Value    Pr > F

FAIL               1   141.09562066   141.09562066    0.52    0.4847

Tests of Hypotheses using the Type I MS for SUBJ as an error term

Source             DF      Type I SS    Mean Square   F Value    Pr > F

MASS*HIPHT           1   205.50904680   205.50904680    0.76    0.4015

Tests of Hypotheses using the Type I MS for SUBJ as an error term

Source             DF      Type I SS    Mean Square   F Value    Pr > F

WALKAGE*AGE          1   111.10281547   111.10281547    0.41    0.5342


                            T for H0:   Pr > |T|   Std Error of
Parameter            Estimate   Parameter=0           Estimate

INTERCEPT          203.1323055 B      3.71    0.0002    54.69394051
MASS              -9.9915553 B     -2.85    0.0047    3.50953198
HIPHT             -4.0090135 B     -3.24    0.0014    1.23833746
WALKAGE              -0.2984613 B     -0.76    0.4465    0.39154613
AGE               0.7679834 B      1.28    0.2002    0.59806315
FAIL             -0.0868361 B     -0.68    0.4958    0.12732507
                 General Linear Models Procedure

Dependent Variable: LTCL

                            T for H0:   Pr > |T|   Std Error of
Parameter            Estimate   Parameter=0           Estimate

MASS*HIPHT           0.1593694 B      2.95    0.0034    0.05402638
WALKAGE*AGE             0.0070389 B      1.37    0.1706    0.00512337
SUBJ       0         7.5209517 B      2.52    0.0124    2.98935212
           1     -30.9242233 B     -3.22    0.0014    9.59177343
           2       9.9721306 B      1.90    0.0586    5.25131846
           3      17.1563279 B      4.45    0.0001    3.85642714
           4      -2.4948048 B     -0.26    0.7923    9.46612590
           5       6.8681775 B      1.42    0.1569    4.83923743
           6       1.6873489 B      0.26    0.7936    6.44311450
           7      10.0069624 B      3.49    0.0006    2.86788295
           8       3.7860160 B      2.64    0.0089    1.43627630
           9      -6.2918269 B     -1.89    0.0591    3.32048031
           K      17.1159921 B     10.49    0.0001    1.63169076
```

```
          M        0.0000000 B       .      .      .
          N        0.0000000 B       .      .      .
          O        0.0000000 B       .      .      .
          P        0.0000000 B       .      .      .
          Q        0.0000000 B       .      .      .
          S        0.0000000 B       .      .      .
          T        0.0000000 B       .      .      .
          Z        0.0000000 B       .      .      .
OBSTHT                 -0.0794006      -0.36   0.7218   0.22274847
OBSTWD                  -0.7706543      -1.54   0.1257   0.50174990
LEG                    0.0222949       0.02   0.9824   1.00999389
HIPDIF                  0.6857498       4.60   0.0001   0.14923564
FAIL*OBST                0.0009992       0.05   0.9571   0.01853900
OBSTHT*LEG                 -0.0460872      -0.50   0.6166   0.09194566
OBSTHT*HIPDIF               -0.0114138      -2.03   0.0431   0.00561726
LEG*HIPDIF              -0.1317477      -1.79   0.0739   0.07342607
OBST                   2.0271885       1.26   0.2103   1.61461166

NOTE: The X'X matrix has been found to be singular and a generalized inverse
      was used to solve the normal equations.  Estimates followed by the
      letter 'B' are biased, and are not unique estimators of the parameters.
```

Appendix B

Study 1: Means and standard deviations by subject by kinematic variable.

Table 6: Leading Toe Clearance

			Obstacle 1		Obstacle 2		Obstacle 3		Obstacle 4	
Age	WalkExp	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
27	11	B	12.88	1.23	19.30	3.60	8.01	4.35	19.57	.
23	12	A	2.41	0.53	.	.	2.33	.	.	.
26	13	S	10.74	3.46	9.70	5.07	11.19	3.42	11.36	3.22
31	14	I	13.85	3.70	16.33	7.57	11.00	2.21	10.55	3.49
25	16	F	4.10	.	8.80	1.81	11.06	1.85	10.30	3.99
36	24	C	10.04	3.24	21.10	12.99	13.01	3.45	24.30	8.30
34	25	P	9.67	1.89	10.47	3.15	12.02	1.27	10.25	3.07
36	26	J	6.67	1.83	11.39	1.45	9.49	2.94	11.95	2.03
41	30	M	11.56	0.69	9.22	1.57	13.26	3.12	5.99	1.64
42	30	T	6.82	3.04	12.39	2.70	9.77	2.53	13.36	2.29
43	31	L	9.32	3.01	13.68	0.60	13.97	4.82	14.86	3.42
45	34	G	10.57	2.82	10.15	1.16	15.11	5.79	8.39	4.76
46	35	E	6.79	2.31	7.76	4.50	6.24	3.32	6.40	1.79
54	37	O	12.78	4.47	10.39	2.69	11.04	0.83	8.47	3.06
56	43	H	11.91	2.09	11.62	2.63	10.24	2.73	11.43	2.48
69	44	N	10.08	4.87	11.25	3.60	8.16	3.51	8.97	2.18
60	47	D	5.64	1.87	6.77	6.13	7.00	1.79	5.23	3.70
60	50	K	28.03	5.84	26.76	3.56	21.46	7.04	22.56	6.78
70	58	Q	14.83	3.65	13.22	2.43	10.82	3.06	13.71	8.20

Table 7: Trailing Toe Clearance

			Obstacle 1		Obstacle 2		Obstacle 3		Obstacle 4	
Age	WalkExp	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
27	11	B	7.49	1.39	17.78	5.61	7.23	5.52	22.67	4.36
23	12	A	.	.	.	.	9.19	.	.	.
26	13	S	10.71	3.66	11.73	3.90	6.47	2.64	9.02	4.41
31	14	I	7.82	2.28	9.80	7.59	12.32	1.76	12.22	2.91
25	16	F	13.40	.	10.01	2.45	8.94	1.56	12.72	4.93
36	24	C	6.25	3.09	12.60	8.10	10.52	5.40	14.53	16.00
34	25	P	9.82	4.81	12.07	4.29	12.34	3.85	11.11	5.13
36	26	J	10.70	5.28	10.26	4.98	12.58	5.81	22.44	7.01
41	30	M	11.40	0.81	16.50	4.26	16.27	1.39	15.13	3.01
42	30	T	9.37	2.41	21.52	8.92	11.91	5.05	25.45	4.56
43	31	L	8.14	2.17	10.33	5.64	10.87	3.57	11.80	5.82
45	34	G	13.19	5.63	25.57	16.16	11.93	9.13	33.31	6.12
46	35	E	5.14	1.22	20.33	3.05	5.98	5.26	15.88	8.66
54	37	O	9.50	1.14	24.47	6.55	9.87	3.42	16.03	8.17
56	43	H	14.08	2.23	21.38	6.55	11.63	2.48	14.08	6.19
69	44	N	11.75	1.45	13.13	3.05	11.36	1.53	20.67	12.80
60	47	D	4.36	2.12	14.13	9.14	4.61	1.51	12.75	5.44
60	50	K	15.95	2.37	15.34	3.23	23.84	7.08	13.51	7.37
70	58	Q	20.48	8.36	25.49	6.03	12.64	4.41	16.40	8.11

Table 8: Leading Hip Elevation.

			Obstacle 1		Obstacle 2		Obstacle 3		Obstacle 4	
Age	WalkExp	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
27	11	B	.	.	46.58	1.05	42.94	2.01	46.40	.
23	12	A	39.41	2.15	.	.	39.98	.	.	.
26	13	S	40.60	0.97	43.09	2.44	40.46	1.79	42.63	2.19
31	14	I	46.33	0.98	48.69	0.23	45.99	0.82	48.22	0.66
25	16	F	.	.	46.22	.	.	.	.	.
36	24	C	50.70	1.12	59.16	1.91	52.62	1.86	56.89	3.39
34	25	P	51.22	1.24	54.91	1.27	52.90	1.42	54.63	0.82
36	26	J	46.41	0.73	55.14	1.83	46.50	1.68	54.70	1.48
41	30	M	51.38	2.10	55.84	1.92	50.12	1.64	53.63	0.79
42	30	T	45.46	1.27	53.25	1.47	46.38	2.77	47.83	11.46
43	31	L	49.35	1.87	51.80	1.16	50.50	1.75	53.21	1.84
45	34	G	54.03	0.81	57.02	0.81	53.83	3.28	56.07	1.38
46	35	E	53.99	1.35	58.32	1.42	55.82	0.99	57.05	1.72
54	37	O	58.95	2.64	62.22	2.04	57.82	1.89	61.14	1.01
56	43	H	57.62	1.14	59.82	1.36	57.36	1.17	61.32	1.95
69	44	N	68.75	2.84	72.78	1.95	68.86	2.49	70.45	2.34
60	47	D	61.63	1.43	62.99	0.01	62.60	0.22	64.96	1.57
60	50	K	57.49	3.10	58.65	2.36	60.33	4.15	60.97	3.18
70	58	Q	63.29	2.46	65.59	1.90	63.86	1.00	68.29	1.22

Table 9: Foot Placement before the Obstacle.

			Obstacle 1		Obstacle 2		Obstacle 3		Obstacle 4	
Age	WalkExp	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
27	11	B	.	.	.	.	25.28	.	.	.
23	12	A	30.70	1.82	.	.	36.48	.	.	.
26	13	S	49.68	2.80	52.64	6.28	55.85	9.83	45.93	9.82
31	14	I	48.26	19.56	36.30	8.91	45.77	15.54	36.75	9.07
25	16	F	39.74	.	23.43	3.20	24.61	9.48	42.14	10.05
36	24	C	53.68	8.42	59.28	10.62	50.29	15.71	53.43	6.56
34	25	P	42.26	10.65	42.59	13.01	48.90	11.67	56.72	19.03
36	26	J	62.63	12.28	53.36	31.89	63.13	16.88	45.71	10.68
41	30	M	29.64	11.74	22.05	4.10	50.86	7.03	30.08	6.98
42	30	T	54.49	12.40	49.15	6.62	45.05	18.10	43.61	12.90
43	31	L	46.90	7.92	54.34	5.85	53.68	7.58	61.35	7.88
45	34	G	63.52	15.97	60.55	3.70	46.99	14.35	52.72	4.72
46	35	E	73.92	18.68	66.99	9.81	59.95	5.33	64.25	6.70
54	37	O	50.81	7.85	53.53	10.45	72.97	19.74	66.63	7.54
56	43	H	77.35	17.52	75.68	9.95	73.41	4.21	71.46	10.78
69	44	N	84.48	15.20	64.35	11.27	79.24	11.17	66.57	20.29
60	47	D	53.90	14.78	59.19	8.20	59.70	5.38	55.61	19.02
60	50	K	62.36	2.40	62.53	3.28	52.69	8.30	55.38	4.46
70	58	Q	72.07	10.50	59.10	17.05	65.15	7.28	55.82	15.65

Appendix C

Study 1: Correlation Matrices by Obstacle.

Table 10: Correlation Matrix - Obstacle # 1

	Gender	FAIL	MASS	AGE	W Exp	LEG	ObstHT	ObstWD	HIPHT	LTCL	TTCL	LHEL	HIPDIFF	FTPL
GENDER	1													
84	0													
FAIL	0.07752	1												
84	0.4834	0												
MASS	-0.42311	0.03769	1											
84	0.0001	0.7336	0											
AGE	-0.49245	-0.1287	0.86824	1										
84	0.0001	0.2434	0.0001	0										
W Exp	-0.4813	-0.1322	0.81565	0.96309	1									
84	0.0001	0.2308	0.0001	0.0001	0									
LEG	-0.21582	-0.0681	0.17831	0.15762	0.11398	1								
84	0.0486	0.538	0.1046	0.1522	0.3019	0								
OBSTHT	-0.34517	-0.0854	0.65416	0.83254	0.81178	0.11935	1							
84	0.0013	0.4398	0.0001	0.0001	0.0001	0.2795	0							
OBSTWD	-0.34517	-0.0854	0.65416	0.83254	0.81178	0.11935	1	1						
84	0.0013	0.4398	0.0001	0.0001	0.0001	0.2795	0.0001	0						
HIPHT	-0.45336	-0.077	0.8404	0.94552	0.88011	0.19019	0.84802	0.84802	1					
84	0.0001	0.4866	0.0001	0.0001	0.0001	0.0831	0.0001	0.0001	0					
LTCL	-0.17157	0.14306	0.38842	0.29873	0.30779	-0.13344	0.25405	0.25405	0.19424	1				
84	0.1186	0.1942	0.0003	0.0058	0.0044	0.2262	0.0197	0.0197	0.0766	0				
TTCL	-0.20092	0.2297	0.47659	0.33911	0.37609	0.16475	0.24161	0.24161	0.1936	0.47894	1			
81	0.0721	0.0391	0.0001	0.002	0.0005	0.1416	0.0298	0.0298	0.0833	0.0001	0			
LHEL	-0.50553	-0.0151	0.82296	0.92195	0.85557	0.30365	0.80358	0.80358	0.95145	0.26472	0.25566	1		
79	0.0001	0.8941	0.0001	0.0001	0.0001	0.0062	0.0001	0.0001	0.0001	0.0176	0.023	0		
HIPDIFF	-0.31057	-0.0539	0.02943	-0.02863	-0.0526	0.15452	0.02486	0.02486	0.01289	0.14066	0.00906	0.16543	1	
80	0.0051	0.6348	0.7955	0.801	0.6431	0.1711	0.8267	0.8267	0.9097	0.2133	0.9368	0.1425	0	
FTPL	-0.09259	0.09821	0.58133	0.53491	0.48826	0.10083	0.54838	0.54838	0.5488	0.11679	0.18144	0.47807	-0.24114	1
80	0.408	0.3801	0.0001	0.0001	0.0001	0.3674	0.0001	0.0001	0.0001	0.2961	0.105	0.0001	0.0312	0

Table 11: Correlation Matrix - Obstacle # 2

	Gender	FAIL	MASS	AGE	W Exp	LEG	ObstHT	ObstWD	HIPHT	LTCL	TTCL	LHEL	HIPDIFF	FTPL
Gender	1													
79	0													
FAIL	0.03144	1												
79	0.7833	0												
MASS	-0.36111	-0.13535	1											
79	0.0011	0.2343	0											
AGE	-0.37282	-0.30225	0.87228	1										
79	0.0007	0.0068	0.0001	0										
W Exp	-0.34773	-0.33308	0.81585	0.96062	1									
79	0.0017	0.0027	0.0001	0.0001	0									
LEG	-0.13766	-0.03006	0.00382	0.01141	0.00872	1								
79	0.2264	0.7926	0.9733	0.9205	0.9392	0								
ObstHT	-0.23723	-0.2948	0.67499	0.82759	0.87979	-0.01118	1							
79	0.0353	0.0084	0.0001	0.0001	0.0001	0.9221	0							
ObstWD	-0.27829	-0.2165	0.6741	0.85079	0.82767	0.14761	0.78466	1						
79	0.013	0.0553	0.0001	0.0001	0.0001	0.1942	0.0001	0						
HIPHT	-0.35022	-0.26161	0.83941	0.94267	0.87286	-0.00077	0.81868	0.85607	1					
79	0.0016	0.0199	0.0001	0.0001	0.0001	0.9946	0.0001	0.0001	0					
LTCL	-0.05335	0.21516	0.10334	-0.03158	-0.02743	-0.36547	-0.12502	-0.10423	-0.0795	1				
79	0.6406	0.0569	0.3648	0.7823	0.8103	0.0009	0.2723	0.3606	0.4863	0				
TTCL	-0.18883	0.04575	0.26954	0.33586	0.36616	0.39545	0.39056	0.43095	0.27928	0.01955	1			
75	0.1047	0.6967	0.0194	0.0032	0.0012	0.0004	0.0005	0.0001	0.0152	0.8678	0			
LHEL	-0.31721	-0.19968	0.84692	0.87042	0.7968	-0.00049	0.81388	0.70929	0.93223	-0.06519	0.22982	1		
73	0.0062	0.0903	0.0001	0.0001	0.0001	0.9967	0.0001	0.0001	0.0001	0.5837	0.0539	0		
HIPDIFF	-0.23162	-0.12974	-0.04279	-0.07673	-0.08598	0.10558	0.16099	-0.07592	-0.0087	-0.10654	0.08803	0.17689	1	
73	0.0486	0.274	0.7193	0.5188	0.4695	0.374	0.1736	0.5232	0.9418	0.3697	0.4654	0.1344	0	
FTPL	-0.01812	0.13289	0.38376	0.44749	0.44645	0.23602	0.50225	0.52411	0.45332	0.02159	0.11038	0.35253	-0.22723	1
73	0.8791	0.2624	0.0008	0.0001	0.0001	0.0444	0.0001	0.0001	0.0001	0.8561	0.356	0.0028	0.0585	0

Table 12: Correlation Matrix - Obstacle # 3

	Gender	FAIL	MASS	AGE	W Exp	LEG	ObstHT	ObstWD	HIPHT	LTCL	TTCL	LHEL	HIPDIFF	FTPL
Gender	1													
83	0													
FAIL	0.03496	1												
83	0.7537	0												
MASS	-0.35484	-0.08393	1											
83	0.001	0.4506	0											
AGE	-0.37747	-0.2734	0.85985	1										
83	0.0004	0.0124	0.0001	0										
W Exp	-0.35156	-0.30481	0.80109	0.96213	1									
83	0.0011	0.0051	0.0001	0.0001	0									
LEG	0.01411	-0.09343	-0.17515	-0.20395	-0.1736	1								
83	0.8993	0.4008	0.1133	0.0644	0.1165	0								
ObstHT	-0.26255	-0.19177	0.62889	0.81944	0.80882	0.03064	1							
83	0.0165	0.0824	0.0001	0.0001	0.0001	0.7833	0							
ObstWD	-0.27533	-0.22684	0.70159	0.88401	0.88296	-0.05097	0.96756	1						
83	0.0118	0.0392	0.0001	0.0001	0.0001	0.6472	0.0001	0						
HIPHT	-0.35653	-0.22798	0.82991	0.94285	0.87664	-0.19538	0.82647	0.88933	1					
83	0.0009	0.0382	0.0001	0.0001	0.0001	0.0767	0.0001	0.0001	0					
LTCL	-0.11019	0.07237	0.09862	0.0407	0.11173	-0.14567	0.00606	0.0195	-0.03491	1				
83	0.3213	0.5156	0.3751	0.7149	0.3146	0.1888	0.9567	0.8611	0.754	0				
TTCL	-0.03833	-0.04215	0.24225	0.15207	0.19818	0.03777	0.0045	0.05246	0.02873	0.49821	1			
83	0.7308	0.7052	0.0274	0.1699	0.0725	0.7346	0.9678	0.6376	0.7966	0.0001	0			
LHEL	-0.39004	-0.32824	0.80845	0.9177	0.86892	-0.09165	0.78466	0.85116	0.94611	0.09077	0.11945	1		
79	0.0004	0.0031	0.0001	0.0001	0.0001	0.4218	0.0001	0.0001	0.0001	0.4263	0.2944	0		
HIPDIFF	-0.2766	-0.23553	0.05028	0.00652	0.02309	0.10852	0.03654	0.07921	0.03675	0.21518	0.14572	0.20073	1	
79	0.0136	0.0367	0.6599	0.9545	0.8399	0.3411	0.7492	0.4877	0.7478	0.0569	0.2001	0.0761	0	
FTPL	0.01077	0.06616	0.48774	0.53461	0.45968	-0.10243	0.45355	0.49403	0.53441	-0.14556	-0.09663	0.42123	-0.00534	1
79	0.925	0.5624	0.0001	0.0001	0.0001	0.369	0.0001	0.0001	0.0001	0.2005	0.3969	0.0002	0.9637	0

Table 13: Correlation Matrix - Obstacle # 4

	Gender	FAIL	MASS	AGE	W Exp	LEG	ObstHT	ObstWD	HIPHT	LTCL	TTCL	LHEL	HIPDIFF	FTPL
Gender	1													
81	0													
FAIL	0.16012	1												
81	0.1533	0												
MASS	-0.38265	-0.05757	1											
81	0.0004	0.6097	0											
AGE	-0.43656	-0.20735	0.86234	1										
81	0.0001	0.0633	0.0001	0										
W Exp	-0.42931	-0.21048	0.80801	0.96107	1									
81	0.0001	0.0593	0.0001	0.0001	0									
LEG	-0.16874	-0.25554	-0.01673	-0.04454	-0.0841	1								
81	0.1321	0.0213	0.8822	0.693	0.4553	0								
ObstHT	-0.32164	-0.11325	0.66719	0.82561	0.87098	-0.13011	1							
81	0.0034	0.3141	0.0001	0.0001	0.0001	0.247	0							
ObstWD	-0.35041	-0.12868	0.6887	0.87489	0.87488	-0.04888	0.8866	1						
81	0.0013	0.2523	0.0001	0.0001	0.0001	0.6648	0.0001	0						
HIPHT	-0.4188	-0.16851	0.82186	0.93811	0.86965	-0.0289	0.81151	0.88014	1					
81	0.0001	0.1326	0.0001	0.0001	0.0001	0.7979	0.0001	0.0001	0					
LTCL	0.01158	0.21228	0.13609	-0.05007	-0.0061	-0.31392	-0.06366	-0.15187	-0.0865	1				
80	0.9188	0.0587	0.2287	0.6592	0.9574	0.0046	0.5748	0.1787	0.4457	0				
TTCL	-0.14539	0.14787	0.1474	0.09264	0.07348	0.1637	0.1751	0.0938	0.09088	0.10711	1			
74	0.2165	0.2086	0.2101	0.4324	0.5338	0.1634	0.1357	0.4267	0.4413	0.3671	0			
LHEL	-0.3944	-0.0854	0.77699	0.85688	0.81178	-0.00258	0.75448	0.76446	0.88391	-0.05121	0.09788	1		
74	0.0005	0.4694	0.0001	0.0001	0.0001	0.9826	0.0001	0.0001	0.0001	0.6648	0.4271	0		
HIPDIFF	-0.24145	0.00747	0.02509	-0.01342	-0.0136	0.0558	0.15628	0.05115	0.02798	-0.0453	-0.0256	0.26226	1	
74	0.0382	0.9496	0.832	0.9097	0.9084	0.6368	0.1836	0.6652	0.813	0.7015	0.8362	0.024	0	
FTPL	-0.19048	0.01119	0.37981	0.43869	0.40803	0.14558	0.48466	0.52705	0.48032	-0.06301	-0.0176	0.4792	0.17778	1
78	0.0948	0.9225	0.0006	0.0001	0.0002	0.2035	0.0001	0.0001	0.0001	0.5837	0.8842	0.0001	0.1324	0

Appendix D

Study 2: Means and Standard Deviations by subject by kinematic measure.

Table 14: Leading toe clearance

			Low-Unres		Low-Rest		High-Unres		High-Rest	
Age	WalkEx	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
26	15	D	1.80	1.05	2.08	1.25	4.02	3.43	6.97	4.43
30	19	P	2.51	1.41	2.51	1.50	5.07	1.89	5.20	1.68
39	22	K	5.55	1.79	4.67	0.79	8.69	2.62	12.05	2.25
38	29	S	5.33	2.21	4.95	1.16	10.38	3.93	12.05	3.94
41	31	F	5.57	0.78	8.27	3.21	12.52	2.41	11.86	2.88
45	33	M	5.49	1.98	5.67	1.79	7.09	2.76	9.36	2.39
46	34	B	6.01	2.52	5.66	0.68	19.78	4.68	19.03	1.41
47	35	H	6.86	2.36	6.40	4.06	13.82	4.86	14.67	4.34
46	35	I	5.87	2.21	5.52	1.95	5.07	1.40	5.39	1.32
51	40	C	3.68	1.01	3.67	2.43	5.74	3.43	9.46	2.13
51	40	E	8.96	1.40	8.78	3.49	12.65	1.33	11.84	1.96
52	41	A	7.39	3.92	8.83	1.93	10.72	2.83	9.25	2.80
58	41	R	6.64	2.39	6.23	1.08	10.65	2.52	9.87	2.32
59	46	J	7.53	1.67	7.10	0.73	11.98	2.10	12.05	2.07
65	55	G	3.55	3.08	4.25	2.02	4.81	3.81	14.51	4.30
68	55	O	4.31	0.86	4.88	1.73	8.69	4.40	12.71	4.54
73	57	Q	6.50	3.46	7.87	5.37	13.01	4.36	10.59	0.94
73	61	L	8.37	2.19	8.58	2.05	6.63	2.23	7.25	1.80
72	62	N	5.45	1.70	6.57	0.84	13.45	1.56	14.40	2.85

Table 15: Trailing toe clearance

			Low-Unres		Low-Rest		High-Unres		High-Rest	
Age	WalkEx	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
26	15	D	2.37	1.22	3.07	0.37	23.37	7.94	16.45	8.93
30	19	P	3.99	0.68	3.98	2.70	12.98	5.16	13.26	4.22
39	22	K	3.42	0.36	3.84	1.26	12.22	6.03	12.13	1.58
38	29	S	5.53	1.84	4.39	2.07	15.14	5.50	15.04	2.94
41	31	F	6.33	0.96	7.81	2.26	13.15	9.39	15.90	3.38
45	33	M	6.48	0.71	6.76	1.73	14.26	5.72	15.36	3.60
46	34	B	6.29	1.23	6.68	1.67	21.26	5.53	14.19	7.13
47	35	H	3.41	0.69	3.17	0.82	10.13	2.42	10.70	2.65
46	35	I	7.17	1.94	7.48	2.54	18.52	4.64	15.93	3.29
51	40	C	3.06	0.35	5.83	1.31	5.51	7.17	10.07	3.63
51	40	E	5.38	1.19	7.32	3.85	14.26	6.30	16.08	3.06
52	41	A	6.19	2.26	6.88	0.97	15.58	3.95	14.55	3.84
58	41	R	5.69	1.69	7.87	3.29	16.81	2.70	16.89	5.77
59	46	J	6.42	1.66	6.34	0.65	16.45	0.95	19.66	4.20
65	55	G	4.50	0.33	5.48	1.87	12.92	4.98	16.73	2.03
68	55	O	5.76	1.71	7.47	1.26	13.79	1.66	21.23	4.51
73	57	Q	7.39	4.57	8.18	4.01	15.95	3.98	13.67	3.42
73	61	L	9.51	1.84	9.62	2.11	22.74	2.73	20.03	3.22
72	62	N	5.64	0.57	7.26	1.30	12.83	9.29	17.22	4.80

Table 16: Leading foot placement prior to the obstacle

			Low-Unres		Low-Rest		High-Unres		High-Rest	
Age	WalkEx	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
26	15	D	61.81	12.93	60.21	7.08	40.91	3.88	52.73	17.65
30	19	P	59.78	5.70	59.59	8.12	73.89	11.15	69.70	10.66
39	22	K	69.02	15.62	80.22	7.58	62.35	12.15	82.26	9.94
38	29	S	84.13	4.32	81.92	8.79	76.93	10.95	83.65	22.01
41	31	F	90.60	7.14	92.37	16.95	73.28	12.22	64.57	6.86
45	33	M	78.15	9.99	71.72	12.67	69.59	17.12	70.11	22.77
46	34	B	86.98	10.69	80.26	6.89	75.40	7.25	71.10	7.71
47	35	H	90.29	19.56	82.52	10.61	96.43	8.71	76.66	3.78
46	35	I	96.52	9.95	90.44	22.89	72.83	12.64	81.97	9.39
51	40	C	91.26	9.84	93.49	9.56	93.31	21.85	82.17	7.47
51	40	E	86.59	14.66	99.07	9.96	105.53	12.59	95.33	6.95
52	41	A	92.82	28.24	83.16	6.81	88.81	4.43	86.39	7.21
58	41	R	84.24	17.29	76.79	28.26	82.86	10.13	78.17	9.11
59	46	J	102.74	12.76	99.07	14.81	98.17	16.65	97.85	11.85
65	55	G	78.21	26.85	77.62	10.10	81.13	11.75	86.05	9.72
68	55	O	85.66	15.85	82.54	4.39	100.08	11.02	100.80	26.19
73	57	Q	103.40	8.65	111.89	19.12	105.09	18.96	106.69	7.31
73	61	L	111.16	4.68	114.39	7.36	110.65	4.55	113.97	8.88
72	62	N	82.11	7.62	88.10	4.87	93.04	17.13	92.66	19.99

Table 17 : Head pitch angle magnitude in Phase 1

			Low-Unres		Low-Rest		High-Unre		High-Rest	
Age	WalkE	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
26	15	d	24.48	22.52	9.45	2.56	16.19	5.62	8.05	3.75
30	19	p	13.33	2.76	10.96	2.81	9.61	5.01	8.41	5.61
39	22	k	21.99	7.67	14.92	8.19	26.29	22.02	22.60	4.24
38	29	s	17.72	12.71	16.89	8.40	17.18	11.87	11.86	6.35
41	31	f	13.30	2.82	12.50	5.14	13.18	4.29	12.18	4.75
45	33	m	18.06	4.33	17.03	8.38	19.58	6.83	18.07	5.39
46	34	b	18.17	10.14	17.25	1.99	18.92	6.53	22.41	4.36
47	35	i	30.66	16.55	29.47	4.57	32.42	13.96	17.00	9.13
46	35	h	8.97	4.34	11.64	.	17.71	12.04	11.56	5.89
51	40	c	13.11	0.13	9.11	5.37	8.61	6.28	9.22	3.43
51	40	e	18.39	11.28	13.65	3.67	18.55	18.67	7.82	5.11
52	41	a	3.71	2.09	6.06	4.68	14.38	9.85	7.89	6.95
58	41	r	17.57	6.43	20.95	11.58	11.07	5.18	20.04	11.01
59	46	j	11.77	9.15	14.95	6.82	12.63	3.27	11.95	4.44
65	55	g	24.17	1.82	13.24	3.65	12.49	7.79	9.42	3.05
68	55	o	18.37	8.35	12.10	6.08	12.85	12.37	17.20	6.73
73	57	q	21.34	27.46	18.13	11.08	13.60	6.83	14.41	7.33
73	61	l	11.63	6.14	10.22	5.84	14.25	3.92	7.74	5.39
72	62	n	5.96	2.29	9.77	3.42	14.57	6.31	14.08	3.47

Table 18: Head Pitch Angle Magnitude in Phase 2

			Low-Unres		Low-Rest		High-Unres		High-Rest	
Age	WalkExp	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
26	15	d	22.12	21.05	7.64	4.53	8.59	7.18	9.27	2.07
30	19	p	10.91	4.41	7.40	5.02	7.41	1.73	4.98	1.19
39	22	k	19.73	11.43	10.64	6.06	8.03	2.95	15.62	4.57
38	29	s	17.12	11.51	17.11	7.52	10.36	3.51	7.83	4.40
41	31	f	9.54	3.15	10.47	9.52	10.16	4.43	8.29	2.87
45	33	m	16.02	4.47	16.94	8.58	17.18	5.30	17.71	5.25
46	34	b	10.47	5.16	8.20	4.05	12.71	7.01	8.69	1.93
47	35	i	25.85	22.51	11.18	2.80	19.16	16.32	15.54	3.97
46	35	h	24.02	13.30	9.37	2.45	7.41	4.05	12.94	1.43
51	40	c	14.27	6.87	18.57	6.10	13.48	4.87	12.19	6.12
51	40	e	7.24	4.16	12.07	5.40	9.58	2.26	8.30	3.59
52	41	a	4.97	2.96	3.80	2.39	6.80	1.24	6.32	3.51
58	41	r	14.99	5.79	19.67	8.34	13.42	3.91	20.23	7.34
59	46	j	13.88	4.99	10.25	2.00	13.18	1.29	10.69	4.97
65	55	g	10.33	3.28	11.61	3.81	12.94	5.34	12.06	8.82
68	55	o	13.09	7.84	21.88	11.34	15.41	4.37	15.17	4.02
73	57	q	15.39	7.25	20.96	8.59	15.26	10.18	27.64	17.82
73	61	l	13.81	6.12	14.53	4.41	11.54	6.07	11.87	4.56
72	62	n	10.43	3.26	6.18	3.18	6.05	1.34	5.49	2.37

Table 19: Head Pitch Angle Magnitude at Pre-Obstacle Phase.

			Low-Unres		Low-Rest		High-Unres		High-Rest	
Age	WalkExp	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
26	15	d	8.58	9.62	4.87	2.23	4.15	1.61	10.42	14.33
30	19	p	6.06	3.40	3.21	2.27	4.12	1.44	2.96	1.10
39	22	k	13.67	12.47	4.26	3.37	5.80	2.12	7.67	4.96
38	29	s	6.94	7.46	8.59	11.29	6.77	2.76	7.75	6.30
41	31	f	6.70	2.81	4.58	1.72	3.69	1.94	2.64	1.76
45	33	m	6.65	2.90	8.07	3.89	7.69	6.38	12.06	11.10
46	34	b	9.73	4.70	7.45	3.81	18.16	5.13	13.67	4.16
47	35	i	5.08	1.98	7.16	2.81	9.03	3.42	10.41	5.77
46	35	h	4.21	3.13	6.07	4.43	12.22	8.72	5.22	3.67
51	40	c	8.50	3.47	9.39	3.22	9.70	3.08	7.65	3.77
51	40	e	6.85	5.65	3.62	2.18	9.60	2.67	6.87	2.82
52	41	a	6.90	3.06	5.97	2.84	7.74	2.60	8.75	2.93
58	41	r	6.79	2.96	6.81	3.65	6.55	2.40	4.88	3.22
59	46	j	8.55	1.34	3.14	2.14	7.52	3.53	4.30	3.55
65	55	g	5.39	2.64	5.38	3.83	8.17	2.73	8.00	4.00
68	55	o	8.09	5.35	4.05	2.44	6.87	4.65	5.25	4.02
73	57	q	5.80	3.08	4.85	3.15	5.25	1.90	8.85	5.55
73	61	l	4.94	1.41	5.05	2.23	10.27	5.94	8.42	3.47
72	62	n	6.69	2.44	2.37	1.58	7.10	3.73	3.59	1.89

Table 20: Head Pitch Angle Magnitude at Post-Obstacle Phase.

			Low-Unres		Low-Rest		High-Unres		High-Rest	
Age	WalkExp	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
26	15	d	16.11	4.21	4.19	1.16	13.68	3.93	17.08	11.12
30	19	p	13.41	3.83	6.60	5.44	20.29	11.94	8.43	5.54
39	22	k	25.10	9.76	17.76	13.75	32.25	18.82	52.30	31.98
38	29	s	18.06	16.84	16.45	11.59	30.20	13.03	22.68	19.22
41	31	f	11.32	3.22	7.88	3.20	15.78	8.18	13.32	4.63
45	33	m	19.16	12.17	16.33	11.31	31.68	19.44	38.39	21.78
46	34	b	18.29	15.35	13.09	8.40	14.98	5.83	11.68	5.92
47	35	i	23.41	10.93	25.99	15.38	29.59	3.51	23.24	7.62
46	35	h	21.63	23.57	15.75	19.54	24.58	11.10	18.88	4.97
51	40	c	11.09	3.23	17.13	9.89	25.46	8.13	24.56	8.82
51	40	e	14.91	1.97	17.67	2.24	23.60	6.60	24.59	1.95
52	41	a	8.19	3.16	5.38	2.71	11.57	6.99	9.33	6.33
58	41	r	14.12	5.61	23.76	12.27	25.75	7.16	30.13	10.46
59	46	j	18.08	9.49	10.21	6.10	21.24	10.06	18.65	13.80
65	55	g	11.64	13.14	6.75	3.40	25.05	11.40	31.14	5.75
68	55	o	26.34	13.00	26.51	9.26	32.59	22.27	26.33	11.10
73	57	q	18.54	7.50	17.86	7.42	36.17	8.87	24.66	11.30
73	61	l	19.36	7.28	18.44	8.67	15.75	9.83	17.26	8.06
72	62	n	12.21	6.07	6.77	4.30	17.54	8.49	10.11	3.68

Appendix E

Study 2: Correlation Matrices of Limb Kinematics by Condition

Table 21: Correlation Matrix - Limb Kinematics - Condition # 1

	EYEHT	MASS	W Exp	AGE	GENDER	FAIL	LEG	LTCL	TTCL	FTPL
EYEHT	1 0									
MASS	0.93163 0.0001	1 0								
W Exp	0.91147 0.0001	0.93783 0.0001	1 0							
AGE	0.92246 0.0001	0.95066 0.0001	0.9881 0.0001	1 0						
GENDER	0.34464 0.0011	0.26022 0.0149	0.21139 0.0494	0.2307 0.0316	1 0					
FAIL	-0.25582 0.0168	-0.22954 0.0325	-0.39915 0.0001	-0.38796 0.0002	0.18639 0.0839	1 0				
LEG	0.2104 0.0505	0.2118 0.0489	0.19192 0.0749	0.16904 0.1175	0.01599 0.8831	-0.08594 0.4287	1 0			
LTCL	0.3563 0.0007	0.26071 0.0147	0.3292 0.0018	0.34101 0.0012	0.08276 0.446	-0.39661 0.0001	0.14053 0.1942	1 0		
TTCL	0.45869 0.0001	0.4553 0.0001	0.4552 0.0001	0.44587 0.0001	0.08463 0.4358	-0.36332 0.0005	0.25 0.0195	0.54342 0.0001	1 0	
FTPL	0.43074 0.0001	0.41179 0.0001	0.36911 0.0004	0.36221 0.0006	0.13985 0.1964	-0.21234 0.0483	0.28524 0.0074	0.32995 0.0018	0.38057 0.0003	1 0

Table 22: Correlation Matrix - Limb Kinematics - Condition # 2

	EYEHT	MASS	W Exp	AGE	Gender	FAIL	LEG	LTCL	TTCL	FTPL
EYEHT	1									
88	0									
MASS	0.92945	1								
88	0.0001	0								
W Exp	0.91	0.9391	1							
88	0.0001	0.0001	0							
AGE	0.9241	0.95229	0.98825	1						
88	0.0001	0.0001	0.0001	0						
Gender	0.30893	0.25628	0.19814	0.21757	1					
88	0.0034	0.0159	0.0642	0.0417	0					
FAIL	-0.22207	-0.17037	-0.32648	-0.32145	0.25741	1				
88	0.0376	0.1125	0.0019	0.0023	0.0155	0				
LEG	0.00043	-0.01357	0.01307	0.01847	-0.00207	-0.11849	1			
88	0.9968	0.9001	0.9038	0.8644	0.9847	0.2715	0			
LTCL	0.36627	0.30289	0.34958	0.34877	0.02987	-0.40933	0.07737	1		
86	0.0005	0.0046	0.001	0.001	0.7849	0.0001	0.4789	0		
TTCL	0.42851	0.4452	0.46975	0.47493	0.06785	-0.41394	0.3197	0.51676	1	
86	0.0001	0.0001	0.0001	0.0001	0.5348	0.0001	0.0027	0.0001	0	
FTPL	0.45286	0.38882	0.4114	0.41603	0.02705	-0.28448	0.29615	0.45693	0.39436	1
88	0.0001	0.0002	0.0001	0.0001	0.8024	0.0072	0.0051	0.0001	0.0002	0

Table 23: Correlation Matrix - Limb Kinematics - Condition # 3

	EYEHT	MASS	W Exp	AGE	Gender	FAIL	ObstHT	LEG	LTCL	TTCL	FTPL
EYEHT	1										
92	0										
MASS	0.90827	1									
92	0.0001	0									
W Exp	0.8938	0.93496	1								
92	0.0001	0.0001	0								
AGE	0.90569	0.94872	0.98667	1							
92	0.0001	0.0001	0.0001	0							
Gender	0.34045	0.24661	0.20331	0.2183	1						
92	0.0009	0.0178	0.0519	0.0366	0						
FAIL	-0.17025	-0.15651	-0.31128	-0.30622	0.28701	1					
92	0.1047	0.1362	0.0025	0.003	0.0055	0					
ObstHT	0.67028	0.56003	0.6929	0.70141	-0.00763	-0.31286	1				
92	0.0001	0.0001	0.0001	0.0001	0.9424	0.0024	0				
LEG	-0.17852	-0.18956	-0.22892	-0.21764	0.01993	0.00394	-0.30316	1			
92	0.0887	0.0703	0.0282	0.0372	0.8504	0.9703	0.0033	0			
LTCL	0.20361	0.17621	0.13299	0.143	-0.10667	-0.01228	0.25532	-0.48367	1		
89	0.0556	0.0986	0.2141	0.1813	0.3198	0.9091	0.0157	0.0001	0		
TTCL	-0.01125	0.07888	-0.00932	-0.00459	0.0948	-0.03539	-0.165	0.1585	0.2188	1	
85	0.9186	0.473	0.9325	0.9668	0.3882	0.7478	0.1313	0.1474	0.0455	0	
FTPL	0.56993	0.4466	0.51567	0.51421	0.19942	-0.18045	0.50662	-0.20331	0.32628	-0.11351	1
92	0.0001	0.0001	0.0001	0.0001	0.0567	0.0852	0.0001	0.0519	0.0018	0.301	0

Table 24: Correlation Matrix - Limb Kinematics - Condition # 4

	EYEHT	MASS	W Exp	AGE	Gender	FAIL	ObstHT	LEG	LTCL	TTCL	FTPL
EYEHT	1										
92	0										
MASS	0.92944	1									
92	0.0001	0									
W Exp	0.91566	0.94005	1								
92	0.0001	0.0001	0								
AGE	0.92532	0.95235	0.9879	1							
92	0.0001	0.0001	0.0001	0							
Gender	0.28498	0.23748	0.16703	0.18297	1						
92	0.0059	0.0226	0.1115	0.0809	0						
FAIL	-0.25777	-0.20638	-0.3711	-0.36223	0.27029	1					
92	0.0131	0.0484	0.0003	0.0004	0.0092	0					
ObstHT	0.69484	0.5911	0.71679	0.72541	-0.09716	-0.37787	1				
92	0.0001	0.0001	0.0001	0.0001	0.3569	0.0002	0				
LEG	-0.14822	-0.18344	-0.15611	-0.13811	-0.04352	-0.1234	-0.09275	1			
92	0.1585	0.0801	0.1373	0.1892	0.6804	0.2412	0.3792	0			
LTCL	0.13611	0.21907	0.18147	0.17966	-0.02254	0.16602	0.2009	-0.44557	1		
87	0.2087	0.0415	0.0925	0.0959	0.8358	0.1243	0.0621	0.0001	0		
TTCL	0.209	0.30317	0.32348	0.31648	0.18988	-0.13371	0.10079	-0.05566	0.07195	1	
88	0.0507	0.0041	0.0021	0.0027	0.0764	0.2142	0.3501	0.6065	0.5103	0	
FTPL	0.57625	0.53178	0.57235	0.57831	0.07315	-0.23935	0.47866	0.05286	0.01848	0.10787	1
92	0.0001	0.0001	0.0001	0.0001	0.4883	0.0216	0.0001	0.6168	0.8651	0.3172	0

Appendix F

Study 2: Correlation Matrices of Head Motion by Condition

Table 25: Correlation Matrix - Head Motion - Condition # 1

	EYEHT	MASS	W Exp	AGE	Gender	FAIL	LEG	PH1M	PH2M	PREM	POSTM
EYEHT	1										
79	0										
MASS	0.9215	1									
79	0.0001	0									
W Exp	0.90402	0.937	1								
79	0.0001	0.0001	0								
AGE	0.91446	0.94854	0.98696	1							
79	0.0001	0.0001	0.0001	0							
Gender	0.41224	0.31567	0.29625	0.31121	1						
79	0.0002	0.0046	0.008	0.0052	0						
FAIL	-0.21256	-0.1662	-0.33271	-0.32982	0.19384	1					
79	0.06	0.1432	0.0027	0.003	0.087	0					
LEG	0.27898	0.25876	0.23075	0.19966	-0.00389	-0.09852	1				
79	0.0128	0.0213	0.0408	0.0777	0.9728	0.3877	0				
PH1M	-0.19789	-0.13687	-0.19136	-0.16936	0.12549	0.16661	0.06908	1			
71	0.0981	0.2551	0.1099	0.158	0.2971	0.1649	0.5671	0			
PH2M	-0.04467	-0.10613	-0.13726	-0.11582	0.07572	0.08081	0.0257	-0.03901	1		
79	0.6959	0.3519	0.2277	0.3094	0.5072	0.479	0.8221	0.7467	0		
PREM	-0.17796	-0.09059	-0.1451	-0.11532	-0.15991	0.03121	-0.05593	-0.11794	0.15486	1	
79	0.1166	0.4272	0.202	0.3115	0.1592	0.7848	0.6244	0.3273	0.173	0	
POSTM	0.0573	0.06811	0.0235	0.04785	0.1192	0.10016	0.09786	0.24659	0.25425	0.09634	1
79	0.6159	0.5509	0.8371	0.6754	0.2954	0.3798	0.3909	0.0382	0.0238	0.3983	0

Table 26: Correlation Matrix - Head Motion - Condition # 2

	EYEHT	MASS	W Exp	AGE	Gender	FAIL	LEG	PH1M	PH2M	PREM	POSTM
EYEHT	1										
82	0										
MASS	0.93645	1									
82	0.0001	0									
W Exp	0.9108	0.93572	1								
82	0.0001	0.0001	0								
AGE	0.9248	0.95023	0.98745	1							
82	0.0001	0.0001	0.0001	0							
Gender	0.30943	0.25344	0.19467	0.21522	1						
82	0.0047	0.0216	0.0797	0.0522	0						
FAIL	-0.22701	-0.15602	-0.33368	-0.32575	0.23687	1					
82	0.0403	0.1616	0.0022	0.0028	0.0321	0					
LEG	-0.03081	-0.07434	-0.05575	-0.0516	0.04539	-0.05259	1				
82	0.7835	0.5069	0.6189	0.6452	0.6856	0.6389	0				
PH1M	0.01816	-0.01357	-0.06006	-0.02101	0.09925	0.03411	0.05055	1			
80	0.873	0.9049	0.5966	0.8533	0.3811	0.7639	0.6561	0			
PH2M	0.31341	0.27933	0.20322	0.24472	0.41794	-0.00864	0.03291	0.16863	1		
82	0.0041	0.011	0.0671	0.0267	0.0001	0.9386	0.7691	0.1349	0		
PREM	-0.05208	-0.10877	-0.1315	-0.13385	0.06772	-0.00442	0.21828	0.1483	0.38521	1	
82	0.6421	0.3307	0.239	0.2306	0.5455	0.9686	0.0488	0.1893	0.0004	0	
POSTM	0.21401	0.16426	0.14035	0.1875	0.25126	-0.06407	0.07376	0.28646	0.51302	0.19415	1
82	0.0535	0.1403	0.2085	0.0916	0.0228	0.5674	0.5102	0.01	0.0001	0.0805	0

Table 27: Correlation Matrix - Head Motion - Condition # 3

	EYEHT	MASS	W Exp	AGE	Gender	FAIL	LEG	PH1M	PH2M	PREM	POSTM
EYEHT	1										
89	0										
MASS	0.90423	1									
89	0.0001	0									
W Exp	0.88318	0.93621	1								
89	0.0001	0.0001	0								
AGE	0.89633	0.95044	0.98561	1							
89	0.0001	0.0001	0.0001	0							
Gender	0.41051	0.30002	0.26474	0.28084	1						
89	0.0001	0.0043	0.0122	0.0077	0						
FAIL	-0.13717	-0.12415	-0.26697	-0.26628	0.29171	1					
89	0.1999	0.2464	0.0114	0.0117	0.0055	0					
LEG	-0.15101	-0.17971	-0.21012	-0.1963	0.01062	-0.03568	1				
89	0.1578	0.092	0.0481	0.0652	0.9213	0.7399	0				
PH1M	-0.16881	-0.15822	-0.15955	-0.1467	-0.07211	0.00879	0.14879	1			
83	0.1271	0.1531	0.1497	0.1857	0.5171	0.9372	0.1794	0			
PH2M	0.13093	0.16454	0.12377	0.14041	0.15202	-0.09408	-0.0971	0.10481	1		
89	0.2213	0.1234	0.2479	0.1894	0.155	0.3805	0.3654	0.3457	0		
PREM	0.09881	0.05084	0.07268	0.06064	-0.01857	0.05525	-0.2876	-0.04694	0.06933	1	
89	0.3569	0.6361	0.4985	0.5724	0.8629	0.6071	0.0063	0.6735	0.5186	0	
POSTM	0.09778	0.0719	0.01979	0.05898	0.24697	0.12936	0.14228	0.25634	0.38012	0.11071	1
89	0.362	0.5031	0.854	0.583	0.0196	0.227	0.1835	0.0193	0.0002	0.3017	0

Table 28: Correlation Matrix - Head Motion - Condition # 4

	EYEHT	MASS	W Exp	AGE	Gender	FAIL	LEG	PH1M	PH2M	PREM	POSTM
EYEHT	1										
86	0										
MASS	0.92399	1									
86	0.0001	0									
W Exp	0.90827	0.93547	1								
86	0.0001	0.0001	0								
AGE	0.9176	0.94865	0.98607	1							
86	0.0001	0.0001	0.0001	0							
Gender	0.33	0.26252	0.2099	0.22453	1						
86	0.0019	0.0146	0.0524	0.0377	0						
FAIL	-0.18588	-0.12644	-0.30362	-0.29285	0.29688	1					
86	0.0866	0.246	0.0045	0.0062	0.0055	0					
LEG	-0.11954	-0.1462	-0.11652	-0.09683	-0.02381	-0.17504	1				
86	0.273	0.1792	0.2853	0.3751	0.8277	0.107	0				
PH1M	-0.08381	0.00038	-0.08925	-0.01878	-0.0603	0.13614	-0.01897	1			
84	0.4485	0.9973	0.4195	0.8653	0.5858	0.2169	0.864	0			
PH2M	0.31088	0.29184	0.17875	0.25869	0.30211	0.02732	0.05607	0.14406	1		
86	0.0036	0.0064	0.0996	0.0162	0.0047	0.8028	0.6081	0.1911	0		
PREM	-0.06613	-0.03852	-0.0882	-0.08772	0.06898	0.09171	0.05195	-0.05193	0.07845	1	
86	0.5452	0.7247	0.4193	0.4219	0.528	0.401	0.6348	0.639	0.4728	0	
POSTM	-0.10019	-0.08181	-0.11132	-0.0419	0.17469	0.05057	0.27027	0.29122	0.31311	0.05835	1
86	0.3587	0.4539	0.3075	0.7017	0.1077	0.6438	0.0118	0.0072	0.0033	0.5936	0

Appendix G

Study 3: Means and Standard Deviations by subject by kinetic variable.

Table 29: Ankle Muscle Moment.

			Obstacle 1		Obstacle 2		Obstacle 3		Obstacle 4	
Age	WalkExp	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
23	12	A	0.054	.	.	.	.	.	.	.
26	13	S	0.059	0.006	0.040	.	0.055	.	0.055	0.017
31	14	I	0.069	0.023	0.047	0.003	0.065	0.001	0.048	0.014
36	24	C	-2.759	4.095	0.092	0.025	0.123	0.083	-0.224	0.364
36	26	J	0.036	0.013	0.117	0.029	0.096	0.012	0.046	0.044
41	30	M	0.005	.	.	.	.	.	.	.
42	30	T	0.083	0.025	0.077	.	0.084	0.025	0.053	.
43	31	L	0.089	0.021	0.090	0.038	0.098	0.030	0.096	0.017
45	34	G	0.101	0.020	0.087	0.060	0.098	.	0.075	0.042
46	35	E	0.099	0.013	.	.	.	.	0.097	0.005
54	37	O	0.136	0.012	0.138	.	0.135	0.041	0.102	0.002
56	43	H	0.110	.	0.088	.	0.110	.	0.116	0.016
69	44	N	.	.	0.160	0.075	0.188	0.020	0.159	.
60	47	D	0.114	.	.	.	0.072	0.053	0.092	.
60	50	K	0.151	0.158	0.033	0.071	0.089	0.042	0.012	0.056
70	58	Q	0.184	.	.	.	0.172	0.035	0.106	0.061

Table 30: Knee Muscle Moment.

			Obstacle 1		Obstacle 2		Obstacle 3		Obstacle 4	
Age	WalkExp	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
26	13	S	-0.129	0.186	-0.381	.	-0.061	.	-0.116	0.133
31	14	I	-0.271	0.143	-0.451	0.307	-0.315	0.044	-0.336	0.108
36	24	C	0.020	.	0.591	1.685	-0.404	0.226	-6.414	8.988
36	26	J	-0.344	0.110	-0.361	0.467	-0.426	0.116	-0.430	0.386
41	30	M	-0.023	.	.	.	.	.	.	.
42	30	T	-0.225	0.302	-0.511	.	-0.239	0.278	-0.476	.
43	31	L	-0.130	0.093	-0.007	0.297	-0.139	0.249	-0.226	0.307
45	34	G	-0.105	0.302	-0.197	0.559	-0.113	.	-0.177	0.092
46	35	E	-0.384	0.238	.	.	.	.	-0.571	0.226
54	37	O	-0.456	0.026	-0.766	.	-0.601	0.118	-0.545	0.245
56	43	H	-0.552	.	-0.475	.	-0.948	.	-1.116	0.144
69	44	N	.	.	-0.634	0.523	-0.475	0.347	0.182	.
60	47	D	-0.279	0.286	.	.	-0.187	0.223	-0.842	.
60	50	K	-2.717	2.808	-0.926	1.404	-1.973	1.336	-0.482	1.030
70	58	Q	0.096	.	.	.	-0.466	0.276	-0.274	1.045

Table 31: Hip Muscle Moment.

			Obstacle 1		Obstacle 2		Obstacle 3		Obstacle 4	
Age	WalkExp	Subject	Mean	SD	Mean	SD	Mean	SD	Mean	SD
26	13	S	1.316	0.376	0.934	.	1.392	.	1.498	0.374
31	14	I	0.514	0.652	-0.236	0.328	0.353	0.432	0.506	0.331
36	24	C	-3.381	12.863	-0.621	0.577	0.669	0.887	-21.932	28.090
36	26	J	-0.167	0.523	1.929	1.227	0.554	0.417	0.240	0.722
41	30	M	0.008	.	.	.	.	.	.	.
42	30	T	0.996	0.792	1.184	.	1.247	0.720	1.256	.
43	31	L	0.179	0.202	0.937	0.592	0.356	0.742	0.644	0.696
45	34	G	1.151	1.188	0.177	0.778	0.424	.	1.593	0.510
46	35	E	-0.214	0.881	.	.	.	.	-0.315	1.028
54	37	O	0.357	1.157	0.008	.	-0.701	0.512	0.027	0.609
56	43	H	0.494	.	-0.302	.	0.180	.	0.818	1.025
69	44	N	.	.	1.183	1.986	0.932	0.364	2.886	.
60	47	D	0.138	0.329	.	.	0.711	0.688	0.932	.
60	50	K	0.483	1.382	-1.227	0.652	0.940	.	-0.752	0.877
70	58	Q	1.294	.	.	.	1.821	0.809	1.444	0.491

Appendix H

Study 3: Correlation Matrices by Obstacle.

Table 32: Correlation Matrix - Obstacle # 1

	Gender	FAIL	MASS	AGE	W Exp	ObstHT	ObstWD	HIPHT	Ankle	Knee	Hip
Gender	1										
39	0										
FAIL	0.03498	1									
39	0.8326	0									
MASS	-0.44145	0.09317	1								
39	0.0049	0.5727	0								
AGE	-0.65849	-0.12521	0.84363	1							
39	0.0001	0.4475	0.0001	0							
W Exp	-0.63988	-0.06269	0.86659	0.9836	1						
39	0.0001	0.7046	0.0001	0.0001	0						
ObstHT	-0.38463	-0.13435	0.6584	0.7946	0.77889	1					
39	0.0156	0.4148	0.0001	0.0001	0.0001	0					
ObstWD	-0.38463	-0.13435	0.6584	0.7946	0.77889	1	1				
39	0.0156	0.4148	0.0001	0.0001	0.0001	0.0001	0				
HIPHT	-0.51053	-0.04137	0.77833	0.92874	0.91325	0.8642	0.8642	1			
39	0.0009	0.8026	0.0001	0.0001	0.0001	0.0001	0.0001	0			
Ankle	-0.17527	-0.12961	0.00764	0.13217	0.12159	0.16514	0.16514	-0.00848	1		
38	0.2926	0.438	0.9637	0.4289	0.4671	0.3218	0.3218	0.9597	0		
Knee	0.19915	0.09453	-0.43092	-0.35054	-0.36918	-0.29113	-0.29113	-0.25972	-0.72545	1	
37	0.2373	0.5779	0.0078	0.0334	0.0245	0.0804	0.0804	0.1206	0.0001	0	
Hip	-0.14422	-0.05693	-0.01538	0.03352	0.02001	0.06336	0.06336	-0.06091	0.88483	0.45194	1
36	0.4014	0.7416	0.9291	0.8461	0.9078	0.7135	0.7135	0.7242	0.0001	0.0064	0

Table 33: Correlation Matrix - Obstacle # 2

	Gender	FAIL	MASS	AGE	W Exp	ObstHT	ObstWD	HIPHT	Ankle	Knee	Hip
Gender	1										
24	0										
FAIL	0.10103	1									
24	0.6386	0									
MASS	-0.5002	-0.16031	1								
24	0.0128	0.4543	0								
AGE	-0.67933	-0.20566	0.93662	1							
24	0.0003	0.335	0.0001	0							
W Exp	-0.70725	-0.05008	0.84181	0.93061	1						
24	0.0001	0.8162	0.0001	0.0001	0						
ObstHT	-0.66392	0.26314	0.7519	0.81793	0.90134	1					
24	0.0004	0.2141	0.0001	0.0001	0.0001	0					
ObstWD	-0.488	0.03592	0.35437	0.48196	0.49666	0.46158	1				
24	0.0156	0.8677	0.0893	0.0171	0.0136	0.0232	0				
HIPHT	-0.55201	-0.0806	0.95704	0.93861	0.80842	0.79209	0.41011	1			
24	0.0052	0.7081	0.0001	0.0001	0.0001	0.0001	0.0465	0			
Ankle	-0.12716	0.19866	0.29191	0.26032	0.10614	0.28097	-0.06427	0.39759	1		
24	0.5538	0.3521	0.1663	0.2192	0.6216	0.1835	0.7654	0.0544	0		
Knee	0.19654	0.26637	-0.28932	-0.31978	-0.31428	-0.1588	-0.18325	-0.21922	-0.13452	1	
23	0.3688	0.2192	0.1806	0.1369	0.1442	0.4693	0.4026	0.3149	0.5406	0	
Hip	-0.05922	0.18154	-0.00816	-0.04028	-0.1268	-0.04379	-0.0734	-0.0222	0.67761	-0.10341	1
21	0.7987	0.431	0.972	0.8624	0.5839	0.8505	0.7519	0.9239	0.0007	0.6556	0

Table 34: Correlation Matrix - Obstacle # 3

	Gender	FAIL	MASS	AGE	W Exp	ObstHT	ObstWD	HIPHT	Ankle	Knee	Hip
Gender	1										
33	0										
FAIL	0.48078	1									
33	0.0046	0									
MASS	-0.47653	-0.13129	1								
33	0.0051	0.4664	0								
AGE	-0.71446	-0.33021	0.87669	1							
33	0.0001	0.0605	0.0001	0							
W Exp	-0.69627	-0.24667	0.79561	0.94553	1						
33	0.0001	0.1664	0.0001	0.0001	0						
ObstHT	-0.58446	-0.20534	0.65204	0.84354	0.82495	1					
33	0.0004	0.2517	0.0001	0.0001	0.0001	0					
ObstWD	-0.63835	-0.17509	0.74001	0.90942	0.8805	0.95912	1				
33	0.0001	0.3298	0.0001	0.0001	0.0001	0.0001	0				
HIPHT	-0.57192	-0.20529	0.85302	0.92963	0.81715	0.80509	0.88966	1			
33	0.0005	0.2518	0.0001	0.0001	0.0001	0.0001	0.0001	0			
Ankle	-0.26325	0.0514	0.67504	0.55145	0.44284	0.36183	0.44795	0.60708	1		
33	0.1388	0.7764	0.0001	0.0009	0.0099	0.0385	0.0089	0.0002	0		
Knee	0.08915	0.02522	-0.31457	-0.27875	-0.33865	-0.32899	-0.347	-0.2109	-0.14017	1	
33	0.6217	0.8892	0.0746	0.1162	0.0539	0.0616	0.0479	0.2387	0.4366	0	
Hip	-0.08327	-0.21733	0.31863	0.19423	0.25335	-0.0179	-0.01516	0.09377	0.37243	0.22675	1
32	0.6505	0.2321	0.0755	0.2868	0.1618	0.9225	0.9344	0.6097	0.0358	0.212	0

Table 35: Correlation Matrix - Obstacle # 4

	Gender	FAIL	MASS	AGE	W Exp	ObstHT	ObstWD	HIPHT	Ankle	Knee	Hip
Gender	1										
37	0										
FAIL	0.08724	1									
37	0.6076	0									
MASS	-0.41265	-0.17643	1								
37	0.0111	0.2962	0								
AGE	-0.62319	-0.32095	0.88674	1							
37	0.0001	0.0528	0.0001	0							
W Exp	-0.60102	-0.25875	0.86852	0.97068	1						
37	0.0001	0.122	0.0001	0.0001	0						
ObstHT	-0.15521	-0.08131	0.48942	0.48682	0.50317	1					
37	0.359	0.6324	0.0021	0.0022	0.0015	0					
ObstWD	-0.43806	-0.26848	0.69889	0.82747	0.82343	0.61892	1				
37	0.0067	0.1081	0.0001	0.0001	0.0001	0.0001	0				
HIPHT	-0.49832	-0.26772	0.84615	0.92072	0.86509	0.56687	0.86985	1			
37	0.0017	0.1092	0.0001	0.0001	0.0001	0.0003	0.0001	0			
Ankle	-0.25645	-0.14852	0.09141	0.26165	0.22079	0.04084	0.2507	0.14424	1		
37	0.1255	0.3803	0.5905	0.1177	0.1891	0.8103	0.1345	0.3944	0		
Knee	-0.22401	-0.08064	0.03742	0.12767	0.11493	-0.02031	0.1127	0.00785	0.34806	1	
36	0.189	0.6401	0.8285	0.4581	0.5045	0.9064	0.5128	0.9638	0.0375	0	
Hip	-0.24561	-0.11916	0.05349	0.18913	0.17295	0.01726	0.1809	0.03955	0.94897	0.90145	1
36	0.1488	0.4888	0.7567	0.2693	0.3131	0.9204	0.291	0.8188	0.0001	0.0001	0