Doctoral Thesis

Foot trajectory when crossing over irregularly shaped obstacles

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Abstract

The risk of falling during obstacle crossing is assessed based on clearance, which is the distance between the obstacle and the toe when the toe is directly above the obstacle. The obstacles that are encountered daily have a wide variety of shapes. However, most previous studies on walking over obstacles investigated simple shapes with a single leaf height. In this study, the foot trajectory was evaluated when stepping over irregularly shaped obstacles such as staircase-shaped (Experiment 1) and oblique (Experiment 2) obstacles.

Experiment 1: Sixteen healthy young adults performed obstacle-crossing tasks. The obstacle was staircase-shaped, combined with a rectangular obstacle with a height of 9.0 cm on the contralateral leg side and a rectangular obstacle with a height of 22.5 cm on the ipsilateral leg side. The results revealed that there was greater foot clearance on the ipsilateral side when the obstacle on the contralateral side is higher than the rectangular obstacle.

Experiment 2: Sixteen healthy young adults performed obstacle-crossing tasks. The obstacles had trapezoidal and rectangular shapes when viewed from the frontal plane. The results revealed that the foot control in the mediolateral direction was adapted to the shape of the obstacle.

The foot trajectory of the lower limb in obstacle avoidance walking was not only determined by the height of the obstacle directly under the foot but may also be influenced by the shape of the opposite leg movement and the shape of the entire obstacle.

Abstract (in Japanese)

障害物跨ぎ越し時の転倒リスクは、障害物とつま先の距離であるクリアランスによって評価される。日常生活における障害物は、様々な形状のものがあり得るが、障害物跨ぎ越し歩行を対象とした殆どの先行研究では、一様な高さを持つ単純な形状の障害物を用いて評価が行われてきた。そこで本研究では、階段状（Experiment 1）や斜め（Experiment 2）といった、不定形な障害物を跨ぐ際の足部軌跡の評価を行った。

Experiment 1：健常な若年成人 16 名を対象に、歩行中に右足、左足の直下の障害物の高さが 9.0 cm の長方形の障害物と右足直下の高さが 22.5 cm、左足直下の高さが 9.0 cm の階段状の障害物を跨ぐ課題を実施した。その結果、後続脚先行脚共に階段状の障害物を跨ぐ際のクリアランスは、長方形の障害物を跨ぐ際のクリアランスと比較して有意に大きくなり、反対脚が跨ぐ障害物の高さの影響を受けることが示された。

Experiment 2：健常な若年成人 16 名を対象に、歩行中に前額面から見て台形の障害物と長方形の障害物の 2 つの形状の障害物を跨ぐ課題を実施した。その結果、障害物の形状に応じて左右方向の足部軌跡が制御されることが明らかとなった。

このことから、障害物跨ぎ越し歩行における下肢の足裏軌道は、足裏直下の障害物の高さによってのみ決定されるのではなく、反対脚の運動や障害物全体の形状を考慮することによって制御される可能性があることがわかった。

Contents

Chapter 1.

General Introduction

Abstract

Locomotion is an essential ability for the survival of animals. They use various means of locomotion, of which walking is the most common form performed by mammals. Among mammals, humans are the only animals that habitually engage in bipedal locomotion, and walking is the main means of locomotion for humans. Human gait is often adapted depending on the environment, even when the environment is new or unpredictable. To perform such adaptive walking locomotion, visual information is necessary. To safely perform a particular type of adaptive gait, i.e., traversing obstacles, it is necessary to instantly determine the shape and position of obstacles that appear in a walking path based on visual information, and control the lower limbs according to the shape of the obstacle to be crossed. The results of previous studies on the traversal of obstacles suggest that the foot trajectory depends on the shape of the obstacle, considering the trade-off between minimizing energy cost and the risk of contact with the obstacle, as well as the motion of the opposite limb.

Based on these findings, it is hypothesized that the foot trajectory can be controlled in vertical and lateral directions by considering the height of the obstacle traversed by the opposing leg, the motion of the opposing leg, and the shape of the obstacle. The objective of this study was to determine whether the foot trajectory during obstacle crossing is influenced by the shape of the obstacle.

Chapter 1.
General Introduction

Abstract (in Japanese)

動物の生存には移動能力が必要不可欠である。哺乳類は様々な移動手段を用いているが、その中でも歩行は最も一般的な移動手段である。哺乳類の中で常習的直立二足歩行をするのはヒトだけであり、歩行はヒトの主な移動手段である。ヒトの歩行は、新しい環境や予測不可能な環境であっても、環境に応じて適応的に変化することができる。このような適応的な歩行運動を行うためには、視覚情報が必要である。適応歩行の一つである障害物跨ぎ越し歩行を安全に行うためには、歩行経路に現れる障害物の形状や位置を視覚情報に基づいて瞬時に判断し、跨ぐ障害物の形状に応じて下肢を制御する必要がある。障害物横断に関する先行研究の結果から、障害物の形状に応じて、エネルギーコストの最小化と障害物との接触リスクのトレードオフを考慮し、反対側の四肢の運動を考慮した足運びを行うことが示唆されている。

これらの知見に基づき、対向脚が通過する障害物の高さ、対向脚の運動、障害物の形状を考慮することで、足部軌跡を上下・左右方向に制御することが可能であると考えられる。本研究では、障害物横断時の足部軌跡が障害物の形状に影響されるかどうかを明らかにすることを目的とした。

1. Mobility is an indispensable ability for survival in animals

Animals must move in search of food. This voluntary animal movement is called locomotion, which is specific to a specie and closely related to the habitat and its body morphology. Animals use various forms of locomotion, such as flying, crawling, swimming, running, and walking. Walking is one of the most common forms of locomotion among mammals, and humans are the only animals that have acquired habitual upright bipedal locomotion. Our hominid ancestors began bipedal walking approximately 6–7 million years ago [1]. One hypothesis that accounts for this evolutionary adaptation is the lower energy requirement compared to quadrupedalism [2]. However, this remains a hypothesis, and the selection pressure for bipedalism in humans remains unknown.

Given that humans habitually walk on two legs, they have physical characteristics that distinguish them from other primates. One of the differences in the body structure of humans and chimpanzees is the shape of the pelvis. Bipedal locomotion requires the support of the head and the upper body above the ground in humans, whereas chimpanzees do not. Thus, the iliac wing of a chimpanzee's pelvis is almost flat, whereas the human pelvis has evolved such that the iliac wing protrudes widely to the side [3].

Human gait is significantly influenced by the aforementioned unique body structure, which results in the rhythmic and alternating movement of the limbs. As a result of this rhythmic motion, walking is regarded as a form of stereotypic locomotion. However, even when the environment is new or unpredictable, humans can adapt appropriately and perform walking locomotion. Therefore, it is evident that humans gradually modify their locomotion to adapt to changes in the environment.

2. Visual information is necessary for humans to perform adaptive walking

When humans perform locomotion in complex environments, visual information plays an important role in facilitating appropriate adaptation. Obstacle crossing, an example of adaptive locomotion, is a visually dependent movement [4]. When there is an obstacle in the walking path, an individual must instantly assess visual information, such as the relative position, height, and shape of the obstacle, and the distance from the foot to the obstacle. Visual and somatosensory information is needed to control the lower limbs before traversing an obstacle, as well as during the process of stepping over an obstacle. Moraes et al. (2014) [5] revealed that adjustment of foot placement occurs even before crossing an obstacle and visual information contributes to the effective motor control of the lower limb. It has been reported that the trajectory of the leading foot is immediately modified by visual inspection of the leading limb [6] and that obstacle-crossing behavior is affected by an optical illusion [7,8]. The motion of the lower limb when crossing an obstacle was evaluated using "clearance," which is the vertical distance between the toe and the obstacle [9,10]. Elliot et al. (2009) [7] used an obstacle in combination with a horizontal-vertical illusion to determine how optical illusions affect clearance during the traversal of obstacles. This illusion is one in which a vertical line segment seems to be longer than a horizontal one, even if they are both the same length [11]. Two obstacles were used in the experiment: one with black horizontal line segments on the sides of the obstacle and black vertical line segments on the top of the obstacle ("H condition"), and the other one with black vertical line segments on the sides and black horizontal line segments on the top ("V condition"). The results revealed that the clearance for the V condition was larger than that for the H condition. Other researchers have also reported that the high-contrast black-and-white pattern of the obstacle was the cause of the greater clearance [8].

3. Clearance depends on the energy consumed and the risk of contact with obstacles

Humans use visual information to control their lower limb movements relative to the height and shape of an obstacle. Foot elevation is determined by a trade-off between energy minimization and the risk of obstacle contact (stumbling). Heijnen et al. (2012) [12] reported that the greater the number of trials, the smaller the clearance of the leading and trailing limbs. They also reported that since contact with obstacles did not increase with the number of trials, a decrease in clearance may not be due to physical fatigue but owing to the achievement of energy minimization. This result suggests that under a guaranteed safety condition, individuals prioritize energy minimization strategies rather than reducing the risk of obstacle contact. Conversely, the stair climbing task results in higher clearance to reduce the risk of contact under conditions whereby the memory of the stair height is obscured by gaze aversion [13].

4. Interaction of motor control of the lower limbs during walking over obstacles

Previous research on adaptive locomotion has shown that limb movements are controlled independently [12,14,15]. The motion and feedback of one limb are not used to control the other limb. Heijnen et al. (2012) [12] discovered that obstacle contact occurred more frequently in the trailing leg than in the leading leg. This was interpreted as the independent control of the leading and trailing limb movements. Moreover, the absence of visual information when the trailing limb crosses an obstacle results in high-frequency contact. Based on this concept, the interaction of motor control between the leading and trailing limbs during the traversal of obstacles was not an area of focus but has been discussed for each leading and trailing limb [9,10,16–26]. In addition, from a clinical perspective, certain characteristics such as a narrower step separation, larger toe clearance, and smaller heel clearance were observed in a high-fall-risk group compared to a low-fall-risk group. In addition, the symmetry of the leading and trailing limb clearance was lower in the low-fall-risk group compared to the high-fall-risk group [27].

As previously indicated, several reported adaptive walking studies support the theory that motor control of the leading and trailing limbs are executed independently, and the evaluation of the leading leg (the first leg to step over an obstacle) and the trailing leg (the last leg to step over an obstacle) are independent. However, previous studies on performing certain tasks using the upper limb [28–30], the working memory during obstacle crossing [31], and obstacle crossing in a VR (Virtual Reality) environment [32], suggest that there may be an interaction in the motor control between the leading and trailing limbs. Reaching movement in the upper limb typically involves left-right limb movement. Howard et al. examined the effects of lead-in and follow-through movements on motor memory during an arm extension task [29,30]. They demonstrated that different motor adaptations were associated with identical arm extension movements when different movements were performed immediately before and after the task. Nozaki et al. (2006) [28] showed that novel loads learned in one-handed reaching are partially and not completely transferred to the unlearned upper limb during two-handed reaching. These findings suggest that motor control during arm-reaching is not limited to the controlled movement itself, but depends on the movements performed before and afterward, and by the opposite upper limb. Heijnen et al. [31] showed that during obstacle-crossing gait, the leading leg is controlled based on obstacle information acquirement from visual assessment, whereas the trailing leg is not controlled based on visual information, but on working memories about the obstacle formed by the leading leg before crossing. In addition, Hagio et al. (2020) [32] suggested that the neural resources of limb-specific motor memories in the obstacle-crossing movements of the leading and trailing legs are shared based on visual input about the obstacle and the trajectory of the limb during the crossing. These findings suggest that the interaction of the leading and trailing limbs is accolated with the motor control of the lower limb during obstacle-crossing.

5. *Obstacle shape affects the motor control of the lower limb during obstacle traversal*

Typically encountered obstacles are not always the same height on both sides. For example, the chain connecting two poles in a parking lot is warped in the middle of the chain, and the height that the leading and trailing limbs cross is different. How are the lower limbs controlled when an irregularly shaped obstacle is crossed? As previously indicated, walking over obstacles is visually-dependent locomotion [4]. Patla [9] examined the effects of the height and depth of obstacles on the motor control of the lower limbs. The participants included six healthy young adults, and the obstacle heights were 6.7 cm, 13.4 cm, and 26.8 cm, and the depths were set at 6.7 cm, 13.4 cm, and 26.8 cm, respectively. The results indicated that as the obstacle height increased, the clearance also increased. Moreover, the change in clearance was small as the obstacle width increased. Based on these findings, it can be concluded that the shape of an obstacle determined based on visual assessment is important for motor control of the lower limb during its traversal.

Clearance was influenced by time constraints [25], aging [16,26], cognitive function [19], sex difference [18], and obstacle height and depth [9]. However, any studies used obstacles of the same height on the left and right sides, irrespective of whether the obstacle was a hurdle or a box [10]. Therefore, the interaction between the leading and trailing limbs when crossing obstacles of different heights and shapes remains unclear. Typical obstacles do not always have simple and regular shapes such as those used in laboratory experiments, which include rectangles, and the leading and trailing legs may have to traverse obstacles of different heights. Therefore, it is necessary to conduct an obstacle-crossing gait study in which the subject traverses obstacles with irregular shapes, similar to real-world situations. In addition, in walking over obstacles, it is necessary to attain appropriate clearance in the vertical direction to avoid contact with them, depending on their shape. During the crossing of an obstacle of the same height on the left and right sides, the risk of foot contact does not change even if the foot is moved in the left or right direction within the width of the obstacle if the foot is in the same elevated position. Therefore, when crossing an obstacle of the same height on the left and right sides, a movement strategy that attempts to reduce the risk of contact with the obstacle by controlling the foot in the vertical direction may be utilized. However, when crossing a trapezoidal obstacle, for which the height differs from left to right and the top of the obstacle is tilted to either side, the risk of contact with either the little finger or the thumb increases when the foot is moved in the left or right direction within the width of the obstacle, even though the foot elevation is the same. Therefore, when crossing an irregularly shaped obstacle such as a trapezoidal obstacle, a movement strategy that reduces the risk of contact by controlling the foot motion in the mediolateral direction rather than in the vertical direction should be utilized. As such, it is conceivable that humans control the lower limb movement in response to different obstacle shapes by adapting their locomotion to the shape of each obstacle.

6. The hypothesis and objectives of this study

In previous studies, the shape of the obstacle was rectangular, and the height and depth of the rectangular obstacle had been shown to affect the foot trajectory. However, obstacles that are typically encountered are not necessarily rectangular but may be irregularly shaped, such as trapezoids. Therefore, the purpose of this study was to determine whether the trajectory of the foot is influenced by the shape of an obstacle during its traversal. We hypothesize that (1) there is an interaction in the motor control between the leading and trailing limbs, (2) obstacle height on the opposite leg side and the motion of the opposing leg affects clearance, and (3) the motion of the lower limb is controlled in the vertical and lateral directions considering the overall shape of the obstacle.

Chapter 2.
Review of the Literature

Abstract

Several studies have shown that the control of walking locomotion across obstacles, which can usually be performed without difficulty by normal adults, is a complex process that involves a wide range of functions. Even if the task appears to be the same in the sense of crossing an obstacle of the same height, it is completely different depending on the context, such as the requirement of cognitive resources, the presence of obstacles, and the shape of the obstacles. Given that there are an infinite number of variations in complexity, i.e., the context to incorporate in a study, the contexts that are presented may not be the most important. It is important to accumulate evidence by researching to clarify the effects of obstacle shape on foot trajectory, for which evidence is lacking, among others, to elucidate the underlying mechanisms of postural gait control and minimize falls in the elderly.

進矢正宏, 三浦有花, 複雑なコンテクストが反映された障害物跨ぎ歩行研究, 理学療法-臨床・研究・教育, 29(1), 3-10, 2022.

Chapter 2.
Review of the Literature

Abstract (in Japanese)

健常な成人であれば問題なく行える障害物を越える歩行運動の制御は、非常に幅広い機能を含む複雑な制御であり、同じ高さの障害物を越えるという意味では同じタスクに見えても、同時に認知資源を必要とするか、他の障害物が存在するか、障害物の形状はどうなっているかなど、コンテクストによって全く異なる運動となることが知られている。すなわち障害物跨ぎ越し歩行は、他の障害物が存在するかどうか、障害物の形状がどのようなものかといった文脈によって、全く異なるものになり得るということである。複雑さのバリエーション、すなわち研究に取り入れるべきコンテクストは無限にあるため、本チャプターで紹介したコンテクストが最も重要であるとは限らない。姿勢歩行制御の根本的なメカニズムを解明と高齢者の転倒を最小限に抑えるためには、中でもエビデンスの不足している障害物の形状が足部軌跡に与える影響を明らかにする研究を行い、エビデンスを蓄積していくことが重要である。

進矢正宏, **三浦有花**, 複雑なコンテクストが反映された障害物跨ぎ歩行研究, 理学療法-臨床・研究・教育, 29(1), 3-10, 2022.

1. Summary

Walking locomotion over an obstacle is a facile task in normal adults that is based on complex control involving a wide range of functions. Even if a task appears to be the same in the sense of crossing an obstacle of the same height, it is completely different depending on various factors such as the presence of other obstacles, the shape of the obstacle, etc. There are an infinite number of factors that should be considered in obstacle-crossing studies. Lower limb motion during overpass gait is evaluated using "clearance," which is the vertical distance between the toe and the obstacle. Clearance is mainly determined by factors such as age, risk of falling, visual information obtained during the crossing of obstacles, and the characteristics of the obstacle such as its height and shape. However, previous studies on overpass gait have not elucidated the effect of obstacle shape on foot trajectory. Typically encountered obstacles do not always have uniform height or shape on both sides. Therefore, it is necessary to perform an over-stepping gait that is more suited to the typical crossing of irregularly shaped obstacles. In this chapter, we will introduce the main determinants of clearance in obstacle-crossing studies and discuss the need to obtain evidence from the perspective of obstacle shape during traversal.

2. Adaptive locomotion

Steady walking locomotion is a rhythmic movement in which the leading and trailing limbs move forward alternately, and the subcortical central nervous system which includes the spinal cord and brainstem is thought to play a major role. However, locomotion is not limited to flat ground and must be executed safely in diverse environments. Such adaptive walking requires contribution from the higher-order central nervous system, such as the processing of sensory inputs from multiple modalities including vision, for the perception of the external environment and the estimation of body state, as well as memory and prediction.

Several studies have been conducted on a variety of adaptive locomotion that targets various populations. For example, Sekiguchi et al. (2022) [33] compared walking on uneven and flat surfaces in stroke patients. Oates et al. (2005) [34] used slippery surfaces and examined the gait-stopping phase. Liss et al. (2022) [35] conducted a study on young adults to determine adaptation to walking on a treadmill in an environment where disturbance is expected. In adaptive walking, the objective is not only to step over an obstacle but also to avoid it [36–42]. Several studies have been conducted based on tasks that specifically reflect contemporary social situations, such as stepping over obstacles while typing text messages on a cell phone [22].

3. Obstacle crossing task

Chen et al. (1991) [43] conducted a study in which 12 young and 12 elderly male and female subjects, 48 subjects in total, were asked to traverse obstacles with heights of 0 mm, 25 mm, 51 mm, and 152 mm. The results showed that in the high obstacle condition, the walking speed when crossing the obstacle was slower and the clearance was greater. There was no significant difference in clearance between the older and younger participants, but the older participants had a significantly slower walking speed when crossing obstacles than the younger participants. This result has been interpreted as a conservative strategy of older adults when compared to younger adults. Patla et al. (1993) [9] conducted a study on the height and depth of obstacles. The subjects were six healthy young adults, and the obstacle heights were set at 6.7 cm, 13.4 cm, and 26.8 cm, and the depths were 6.7 cm, 13.4 cm, and 26.8 cm, respectively. The results indicated that as the height of the obstacle was increased, the clearance increased, but the change in the clearance was minor as the width of the obstacle increased. The findings of these classic studies indicate that lower limb motion in the traversal of obstacles is affected not only by the size of the obstacle in terms of height and width but also by age. In addition, previous studies have shown that motor memory [19,31] and cognitive function [26] are also affected in over-the-obstacle walking.

It is known that the traversal of obstacles requires information such as the position and size of the obstacle, which is obtained visually and is a motor task with high visual dependence, including binocular vision [44]. In an investigation by Patla et al. (2002) [44], the subjects crossed obstacles of different heights placed on a walking path under two conditions: binocular and monocular vision. The results showed that clearance was greater when the subjects crossed the obstacle using monocular vision compared to when they crossed using binocular vision. These results suggest the possibility that the subjects need to raise their feet higher to ensure clearance because they could not assess the exact size of the obstacle using monocular vision, or that the obstacle simply appeared larger than it was in this case. This indicates the importance of obtaining accurate information about obstacles. In addition, during walking motion, the eyes are usually focused approximately three steps forward. As such, in adaptive walking tasks such as walking on a bumpy dirt road or climbing stairs, visual information that was retained as working memory is used as information about the environment, which is necessary for lower limb control that deviates from a normal walking pattern [13,45]. Such complex information processing involves numerous cortical brain regions, including the visual cortex, posterior parietal lobes, and motor cortex [46,47].

4. Obstacle crossing task in VR and AR environments

In recent years, VR (Virtual Reality) and AR (Augmented Reality) technologies have attracted significant attention, and they have been incorporated into obstacle-crossing research. Hagio et al. (2020) [32] asked participants to walk over an obstacle in a VR environment and examined the effect of the visual motion transformation of the leading leg on the foot trajectory of the trailing leg. The results showed that the clearance of both the leading and trailing legs was greater during the crossing of obstacles in a real environment compared to a VR environment. It was also determined that only the clearance of the leading leg exhibited a correlation between the VR environment and the real environment. They also found that when a visuomotor perturbation was applied only to the motion of the leading leg during the crossing of a virtual obstacle, a trajectory correction occurred not only in the toe of the leading limb but also in the toe of the trailing limb. This suggested that the neural resources for lower limb-specific motor memory for obstacle-crossing movements of the leading and trailing legs are shared based on visual input about the characteristics of the obstacle and the trajectory of the limbs during the crossing. Kim et al. (2019) [48] also discovered that learning to walk across an obstacle in a VR environment transferred to learning to walk across an obstacle in a real environment. Kim et al. taught healthy young adult participants to minimize clearance when walking across an obstacle in a VR and a real environment. As a result, they found that the clearance during the traversal of obstacles in a VR environment transitioned to the clearance during the traversal of obstacles in a real environment. Based on this result, they argued that the crossing of obstacles should be performed not only in a real environment but also in a safer VR environment. Binaee et al. conducted a study that involved an obstacle-stepping walking task that involved 14 healthy young subjects in both AR and real environments [49]. The results showed that the clearance of the leading leg during the crossing of the obstacles in the AR environment was larger compared to that of the real environment. In addition, the speed of approaching obstacles was lower in the AR environment compared to the real environment. Based on these findings, it is considered that the VR environment has a higher association with the traversal of obstacles in a real environment than in the AR environment.

The traversal of obstacles in a real environment involves the risk of falling owing to contact, as well as the problem associated with effects that cannot be eliminated. These include the brightness of the lighting in the laboratory where the experiment is conducted, the color of the wallpaper and the floor, and the contrast between the color of the floor and the color of the obstacles. However, these problems can be addressed in a VR or AR environment, and experiments can be conducted more safely compared to a real environment. It is expected that experiments involving the crossing of obstacles in a safer VR environment will be conducted more frequently in the future.

5. Research on obstacle crossing reflecting realistic and complex contexts

In classical studies on obstacle-crossing behavior, an experimental setup was employed in which participants cross a single obstacle placed in the middle of a walking path in a laboratory. However, this simplified situation is not typical in the real world, and it is necessary to control walking behavior to consider the crossing of obstacles for cases involving complex physical or psychological contexts. For example, the number of obstacles may not be limited to one, but there may be situations in which multiple obstacles must be crossed. Krell et al. (2002) [50] conducted an experiment in which healthy young subjects crossed two obstacles placed 1 m, 1.5 m, and 2 m apart, in addition to a single obstacle condition. In the single obstacle condition, the relative position of the foot immediately before crossing the obstacle remained constant, regardless of the distance from the starting point to the obstacle. In contrast, in the two-obstacle condition, the position of the trailing leg before crossing the first obstacle was adjusted according to the distance between the two obstacles. This indicates that the strategy for crossing the second obstacle is planned and executed before crossing the first obstacle.

Silva et al. (2020) [51] compared crossing strategies for two obstacles in 19 healthy older adults and 19 patients with Parkinson's disease. In this study, two obstacles were placed 50 cm and 108 cm apart, in addition to a single obstacle condition. The study focused on the left-right asymmetry of clearance. Note that this index is not the asymmetry of the leading and trailing legs in the same trial, but the asymmetry of the clearance of the trial with the right leg as the leading leg and the clearance of the trial with the left leg as the leading leg. Thus, this index focuses on the difference between the dominant and non-dominant leg in healthy subjects, and the difference between the side with major diseases such as tremors or muscle stiffness, and the side with the minor disease in Parkinson's disease patients, in terms of the difference in the obstacle-crossing movement. Silva et al. (2020) [51] suggested that this may be the result of age-related decline in motor, cognitive, and sensory systems, as well as Parkinson's disease. The Parkinson's disease patients exhibited more asymmetry in clearance, especially in the trailing limb compared to the healthy elderly group. The location of the second obstacle was also shown to affect the clearance asymmetry, and Silva et al. (2020) [51] speculated that the trailing limb clearance asymmetry may be the result of the interference of sensorimotor processing of the second obstacle and the processing for the first obstacle. The task of crossing multiple obstacles has been studied not only in patients with

Parkinson's disease but also in healthy subjects to determine the effects of distance between the obstacles and age on the traversal of multiple obstacles. Wang et al. (2020) [52] conducted a study in which healthy young adults performed a task wherein they each crossed two differently spaced obstacles while walking, to determine their crossing-over motor strategies. It was demonstrated that the vertical distance from the heel of the leading leg to the obstacle was greater and the vertical distance from the toe of the trailing leg to the obstacle was shorter for the second obstacle compared to the first obstacle. Several studies have compared the crossing of obstacles in normal subjects. Berard et al. (2006) [53] performed a task in which 7-year-old children and young adults were asked to traverse two obstacles while walking. They found that the adults used a consistent locomotor strategy when the number of obstacles increased, whereas the children used a conservative locomotor strategy of adjusting the placement of their feet. These findings indicate that the number of obstacles influences the overpass walking strategy.

Human gait, which involves walking on two unstable legs, is thought to involve a relatively greater role of the higher central nervous system compared to quadrupeds. In addition, it is known that interference effects such as a reduction of walking speed can be observed in walking movements when a subject is required to simultaneously perform cognitive tasks such as mental arithmetic. The degree of interference in the dual-task environment is known to be greater in older adults who have experienced falls [54], and was thought to reflect the reduced capacity of the central nervous system for processing in a high-risk group for postural gait control. The performance on the dual task has been described as a promising predictor of future fall risk [55]. As previously indicated, since adaptive locomotion is thought to place a greater load on the higher central nervous system compared to steady walking, several dual-task experiments have been conducted in which the obstacle-crossing task was performed simultaneously with a cognitive task. Soma et al. (2011) [54] divided elderly subjects into two groups, one with the experience of falling and one without the experience of falling, and walking was performed. The results showed that under the dual task condition, the clearance was smaller, and the foot was closer to the obstacle in the group with the experience of falling.

Jehu et al. (2019) [56] conducted a study in which 16 healthy young adults were asked to hold both a transparent box with no visual information restriction and an opaque box with visual information restriction. They compared the toe clearances for both situations and asked the subjects to step over a 20 cm high obstacle. The results showed that walking with the opaque box during obstacle crossing significantly increased clearance compared to walking without the box. In addition, walking with the opaque box significantly increased clearance compared to walking with the transparent box. In addition, walking with the transparent box significantly increased clearance compared to walking without the box. Jehu et al. [56] attributed the increase in the clearance height to the fact that carrying the box limited visual information about the obstacle to one or two steps before it was crossed. They also noted that walking with a loaded opaque box may have increased the difficulty of achieving clearance because of the partially narrowed visual field of the lower limb, making it difficult to calculate the distance to the obstacle. Thus, Jehu et al. [56] argue that carrying a load when stepping over an obstacle and the narrowing of the visual field increase the risk of falling. The increased risk of falling in such a complex environment compared to simple obstacle-crossing with a single obstacle suggests the need for experiments on obstacle traversal in complex environments that better reflect typical scenarios.

6. The purpose statement of the research

Since there are an infinite number of factors that should be reflected in obstacle-crossing gait research, the determinants of clearance introduced in this chapter are not necessarily the most important ones. As the findings presented in this chapter show, previous obstacle-crossing studies have used rectangular obstacles of the same height on both sides, and there is a lack of data related to the shape of an obstacle. Therefore, the purpose of this investigation is to evaluate the effect of obstacle shape on clearance, not only rectangular obstacles, but also stair-shaped obstacles of different heights on the left and right sides, and trapezoidal obstacles.

Chapter 3.
Foot clearance when crossing obstacles of different heights with the lead and trail limbs
(Experiment 1)

Abstract

To predict and prevent falls and fall-related injuries, it is crucial to understand the motor control for crossing obstacles. In real life, since obstacles do not always take regular shapes like rectangles, the lead and trail limbs sometimes need to negotiate different obstacle heights. The interlimb interaction in this process has remained unknown since obstacle-crossing studies commonly use a single-obstacle paradigm in which the obstacle height is the same for the lead and trail limbs. We used a dual-obstacle paradigm to test whether the foot clearance over one obstacle was influenced by the contralateral obstacle's height. Sixteen healthy young male and female participants (age: 22.5 ± 1.9 years) crossed over two obstacles placed side by side. Four obstacle conditions were made by combining obstacles of two heights (low, L, 9.0 cm; high, H, 22.5 cm) of the obstacles. In the LL condition, both obstacles were low, and in the LH condition, there was a low obstacle for the lead limb and a high one for the trailing limb. Similarly, we also arranged HL and HH conditions. Each subject performed twenty trials per condition. We compared the vertical foot clearance, prestep distance, and poststep distance between the conditions. The foot trajectory to step over the obstacles was affected by the contralateral obstacle's height. The vertical foot clearance of the trailing limb was greater in the HL condition than in the LL condition. The vertical foot clearance of the lead limb was greater in the LH condition than in the LL condition. The results suggested that the foot trajectory was not determined exclusively by the obstacle to be crossed. Instead, comprehensive information, including the height of the obstacle for the other limb, might be used for motor control during obstacle crossing.

Yuka Miura, Masahiro Shinya, Foot clearance when crossing obstacles of different heights with the lead and trail limbs, Gait & Posture, 88, 155–160, 2021.

Chapter 3.

Foot clearance when crossing obstacles of different heights with the lead and trail limbs

(Experiment 1)

Abstract (in Japanese)

転倒や転倒に関連する傷害を予測・予防するためには、障害物を越えるための運動制御を理解することが重要である。実生活において、障害物は必ずしも長方形のような規則的な形状をしていないため、時として左右で異なる高さの障害物を跨ぐ必要がある。しかし、障害物跨ぎ越し研究では、障害物の高さが同じである単一障害物実験が一般的であるため、この過程における左右脚間の相互作用は不明なままであった。そこで、我々は 2 障害物実験を行い、一方の障害物を越える際の足のクリアランスが、他方の障害物の高さに影響されるかどうかを検証した。健康な若い男女 16 名（年齢：22.5±1.9 歳）が、並置された2つの障害物の上を横断した。障害物の高さを2種類（低、L, 9.0cm、高、H, 22.5cm）を組み合わせて 4 つの障害物条件を作成した。LL 条件では両方の障害物が低く、LH 条件では先行脚に低い障害物、後続脚に高い障害物が配置された。同様に、HL 条件と HH 条件も配置した。各参加者は 1 条件につき 20 回の試行を行った。条件間でクリアランス、踏み切り前のつま先から障害物までの水平方向の距離、踏み切り後のつま先から障害物までの水平方向の距離を比較した。足部軌跡は、反対脚が跨ぐ障害物の高さに影響された。HL 条件では LL 条件よりも後続脚のクリアランスが大きくなった。また，先行脚のクリアランスは LH 条件で LL 条件よりも大きくなった．この結果から、足部軌跡は横断する障害物のみによって決定されているわけではないことが示唆された。むしろ、反対脚の障害物の高さを含む総合的な情報が、障害物横断時の運動制御に利用されている可能性がある。

Yuka Miura, Masahiro Shinya, Foot clearance when crossing obstacles of different heights with the lead and trail limbs, Gait & Posture, 88, 155–160, 2021.

Introduction

A survey showed that 35% of elderly people reported at least one fall experience in the preceding year, and falls may have a detrimental impact on health, independence, and quality of life [57]. One of the causes of falls is tripping over obstacles [58–61]. To predict and prevent such falls, scientists have investigated strategies and mechanisms of obstacle crossing [62]. In previous studies on obstacle avoidance, the distance from the foot to an obstacle, often called clearance, has been used as a critical parameter in a variety of obstacle-crossing tasks [10,12,31,62,63].

Although these studies used a single obstacle with a certain height and regular shape, real-life environments are complex, and obstacles do not always take regular shapes like rectangles. In such situations, the lead limb and trail limb must negotiate different obstacle heights. Studies of obstacle crossing have commonly used a single-obstacle paradigm in which the height of the obstacle was the same for the left and right [10,64]. In a paradigm with a single, regularly shaped obstacle, the interaction between the lead and trail limbs cannot be studied. Assessing the interactive control of lead and trail limbs when we face environmental challenges (i.e., an obstacle whose height is different on both sides) may help to deeply understand the ability to obstacle avoidance, contributing to preventing tripping over an obstacle.

Recent studies in arm-reaching tasks may provide some insights into the control of the leading and trailing limbs. Howard and his colleagues tested the effect of lead-in and follow-through movements on the motor memory of an arm-reaching task [29,30]. They demonstrated that different motor adaptations could be associated with physically identical arm-reaching movements if different movements were performed just before or after the task. Nozaki et al. (2006) [28] demonstrated that learning a novel load during unimanual reaching was partially, but not completely transferred to the same limb during bimanual reaching. They also reported that one could learn two conflicting force fields if one of them was associated with unimanual and the other with bimanual reaching. These findings suggest that motor control of arm-reaching was not limited to the controlled movement itself but was dependent on the movements that are performed before or after it or performed by the contralateral limb. If this concept can be extended to gait tasks, motor control of the trail/lead limb crossing over an obstacle might be influenced by the movement of the lead/trail limb.

The purpose of this study was to investigate the interlimb interaction in the motor control of limb trajectories during obstacle crossing. We developed a dual-obstacle paradigm in which the heights of the obstacle were not necessarily the same for the lead and trail limbs to this end, we established four experimental conditions as combinations of high and low obstacles (i.e., low-low, low-high, high-low, and high-high) and compared toe clearances between the conditions. We assumed that if the motor control of one limb would be affected by the other side, one would expect different limb trajectories for crossing the same obstacle depending on the height of the contralateral obstacle.

Methods

Participants

Sixteen young, healthy adults participated in this study (eight males and eight females; age: 22.5 ± 1.9 years; height: 165 ± 9.5 cm; weight: 58.2 ± 9.6 kg). Each subject's dominant foot was determined using a modification of the Waterloo Footedness test of Melick et al. (2017) [65]. Fifteen participants were right-footed, and one was left-footed. Participants were free from any impediments to normal locomotion and had normal or corrected-to-normal vision. All participants gave written informed consent, and the study was approved by the local ethics committee of Hiroshima University in Hiroshima, Japan (approval number: 01-31), according to the Declaration of Helsinki.

Experimental protocol

Participants walked barefoot at a self-selected pace along a 7 m walkway and stepped over obstacles. Two obstacles were placed in the middle of the walkway. The participants were instructed to cross the obstacle with the right leg (lead leg) in the fifth step and with the left leg (trail leg) in the sixth step (Figure 3-1-A). Before the experiment, the participants were asked to adjust the starting position without actually crossing over the obstacles. Two different obstacle heights were used (Figure 3-1-B): low (height: 9.0 cm; depth: 29.7 cm; width: 21.0 cm) and high (height: 22.5 cm; depth: 29.7 cm; width: 21.0 cm). Four experimental conditions were arranged by combining the two heights. The condition where the low obstacle was set for the lead leg and the trail leg was termed LL. Similarly, we arranged LH, HL, and HH conditions (Figure 3-1-C). It has been reported that there is a learning effect on stepping parameters in obstacle-crossing studies in the previous study [12]. In the present study, to assess the potential learning effect, we recorded twenty trials for each condition (80 trials in total). No practice trials were conducted before the experimental sessions. The order of the conditions was randomized between the participants.

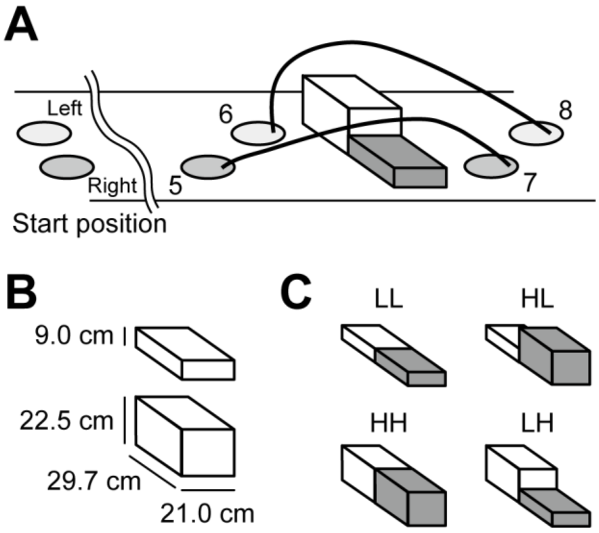

Figure 3-1. Experimental setup. A. Participants were asked to walk on a walkway and cross over obstacles at the 5th and 6th steps. The right leg was always the lead leg (gray). B. Dimensions of the obstacles. We used two obstacles with different heights: 22.5 cm (High: H) and 9.0 cm (Low: L). C. Experimental conditions. We tested four combinations of obstacles (LL, HL, LH, and HH). The grey boxes indicate the obstacles for the lead (right) leg and the white boxes indicate the obstacles for the trail (left) leg. Note that panel A shows the LH condition.

Data collection

We measured the stepping kinematics of each experimental condition. Infrared reflective markers were pasted on sixteen anatomical landmarks on each participant's body: the left and right medial femoral epicondyle, lateral femoral epicondyle, medial malleolus, head of the first metatarsal, head of the fifth metatarsal, and calcaneus. The markers were captured by a 3D optical motion caption system (Qualisys Track Manager, Qualisys, Göteborg, Sweden) with eight cameras (Qualisys-Miqus M3, Qualisys). The sampling frequency of the kinematic data was 250 Hz. The measured signals were stored on a computer, and all numerical calculations were performed using MATLAB 2017b (Math Works, Inc., MA, USA).

Data analysis

In one trial, a participant hit the obstacle with the lead leg in the LH condition. Six participants hit the obstacle with the trail leg in the HL (1 trial), LH (3 trials), and/or HH (3 trials) conditions. The number of obstacle strikes was larger for the high obstacle than for the low obstacle and larger for the trailing limb than for the lead limb. These trials were excluded from the subsequent analyses.

The kinematic data were low-pass filtered using a zero-lag second-order Butterworth digital filter with a cutoff frequency of 20 Hz. The cutoff frequency was determined based on the visual inspection of the experimenter so that the filtered signals reflect the characteristics of the raw data being free from the effect of the noise. The limb trajectory during the obstacle avoidance was quantified for the lead and trail legs by using the following parameters (Figure 3-2). The vertical foot clearance was defined as the distance between the marker placed at the first metatarsal marker and the top of the obstacle when the marker was just above the obstacle. Note that in the calculation of the foot clearance, the vertical offset of the toe marker was compensated. We calculated the prestep and poststep distances.

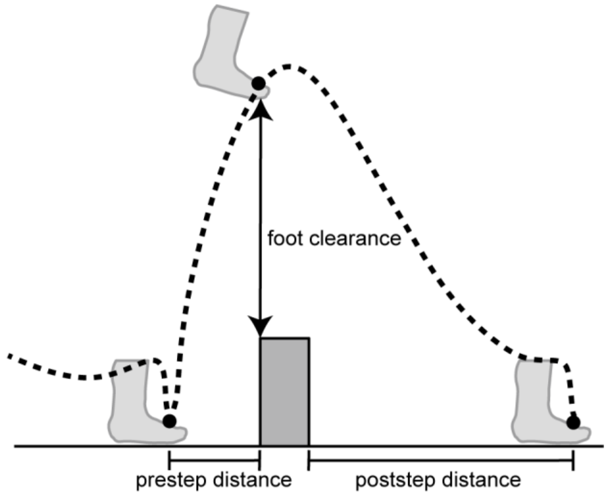

Figure 3-2. Illustration of the vertical foot clearance, prestep distance, and poststep distance. The gray box indicates the obstacle, and the dashed line indicates the trajectory of the leg as the participants crossed over the obstacle.

Statistics

In this study, since we were interested in the effect of the height of the contralateral obstacle on the limb trajectory, we examined pairs of conditions where the height of the obstacle for the lead/trail leg was the same and the contralateral obstacle was different. For instance, the height of the obstacle for the lead leg was the same between the LL and LH (i.e., the lead leg crossed over the low obstacle in both conditions), whereas the obstacle height for the trail leg was different. Similarly, we compared the lead leg trajectories between the HL and HH conditions, and we compared the trail leg trajectories between the LL and HL conditions and between the LH and HH conditions. Because the toe clearance could be decreased as one repeats trials [12], we calculated 5-trial averages of the clearances (i.e., trial numbers 1-5, 6-10, 11-15, and 16-20 were averaged). To test the effects of the obstacle condition and the repetition of the trials on the outcomes, we used two-way repeated-measures ANOVAs (condition * trial). Once a significant interaction was observed, the differences between the obstacle conditions were tested for each of the four epochs of trials. The significance threshold was set to 0.05 for the ANOVAs and Bonferroni correction was used for the posthoc comparisons (0.0125 = 0.05/4). The statistical analyses were performed using JASP (Eric-Jan Wagenmakers, Amsterdam, Netherlands).

Results

The limb trajectories during obstacle crossing were affected by the height of the contralateral obstacle. The limb trajectories of a typical subject and statistical results for the foot clearance are illustrated in Figure 3-3 and Figure 3-4. The descriptive and statistical results for all parameters tested are summarized in Table 1.

The 2-way rmANOVA (LL/HL * trial) revealed that the trail limb trajectory was different between the LL and HL conditions (Figure 3-3-A, C). The participants lifted their trail limb higher in the HL condition than in the LL condition, which was confirmed by the significant main effect of the condition on foot clearance ($F_{(1, 45)} = 5.18, p = 0.04, \eta^2 = 0.26$). A significant main effect of the trial ($F_{(1, 45)} = 4.38, p = 0.01, \eta^2 = 0.23$) indicates that the foot clearance of the trailing limb decreased as subjects repeated the task in the LL and HL conditions. The prestep distance of the trailing limb was longer in the LL condition compared with the HL condition ($F_{(1, 45)} = 8.02, p = 0.01, \eta^2 = 0.35$).

As a result of the 2-way rmANOVA (LH/HH * trial), no significant difference between the LH and HH conditions was observed on the foot clearance of the trailing limb. The condition * trial interaction was significant in the prestep distance. The multiple comparisons show that the LH condition was significantly more significant than the HH condition in prestep distance for Trial 16-20 ($p < 0.05$).

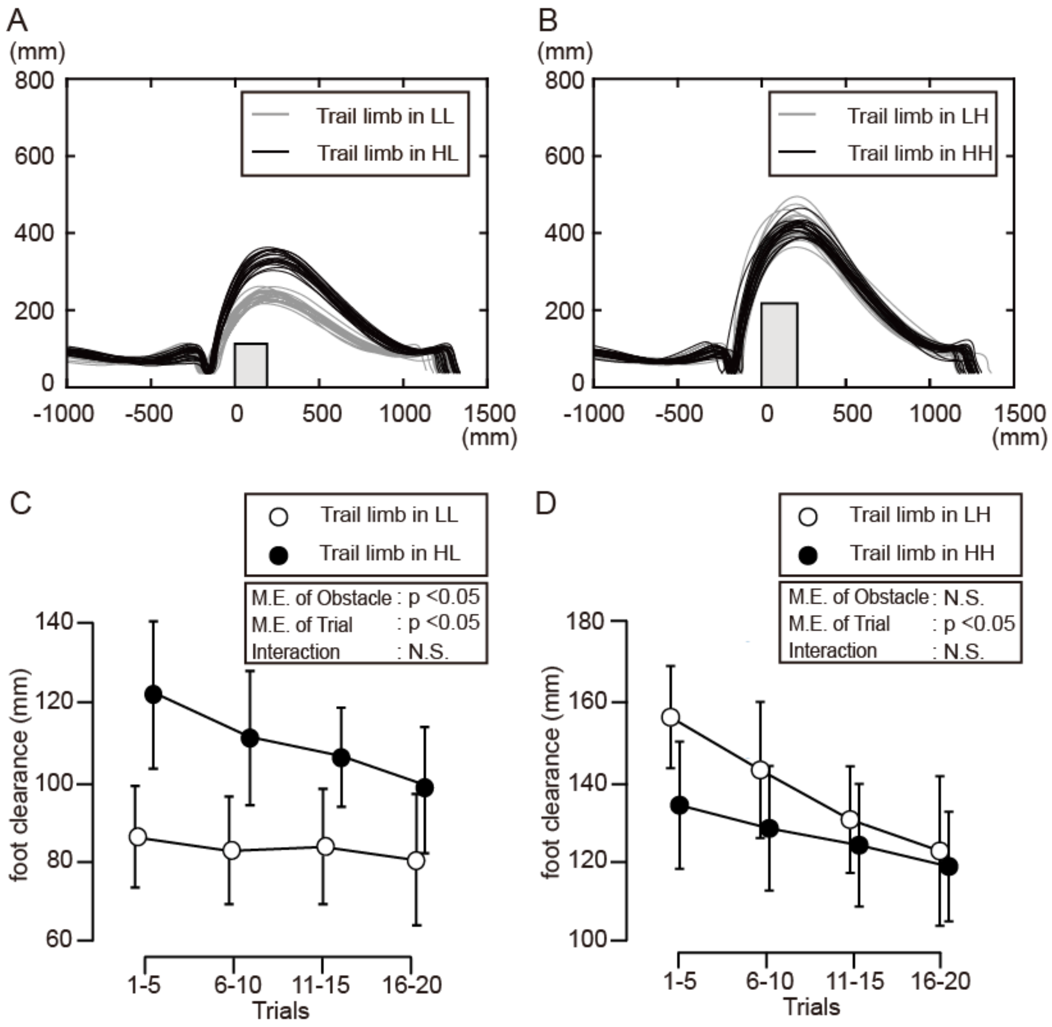

Figure 3-3. Measurement of the foot clearance for the trailing limb. A, B: The trajectories of the marker attached to the head of the first metatarsal of the trail foot for one participant are superimposed. The gray box indicates the obstacle. C, D: The mean values of all subjects and 95% confidence intervals of the foot clearance.

The comparison between the LL and LH conditions revealed that the lead limb trajectory was also influenced by the obstacle height for the trailing limb (Figure 3-4-A, C). The lead limb was lifted higher in the LH condition than in the LL condition ($F_{(1, 45)} = 7.43, p = 0.02, \eta^2 = 0.33$). A significant main effect of the condition was also observed in the poststep distance ($F_{(1, 45)} = 10.1, p = 0.01, \eta^2 = 0.40$). The lead leg clearance decreased with repetition in the LL and LH conditions, which was confirmed by the significant main effect of the trial on the foot clearance ($F_{(1, 45)} = 5.75, p < 0.01, \eta^2 = 0.28$). The poststep distance of the lead limb was longer in the LL condition than in the LH condition. In the 2-way rmANOVA (LL/LH * trial), a significant interaction was observed on the prestep distance ($F_{(3, 45)} = 6.31, p < 0.01, \eta^2 = 0.30$). Multiple comparisons showed no significant differences between the LL and LH conditions.

No significant main effects or interactions were observed in the comparison of the lead limb trajectories between the HL and HH conditions except that poststep distance was larger in the HL condition than in the HH condition ($F_{(1, 45)} = 15.3, p < 0.01, \eta^2 = 0.50$).

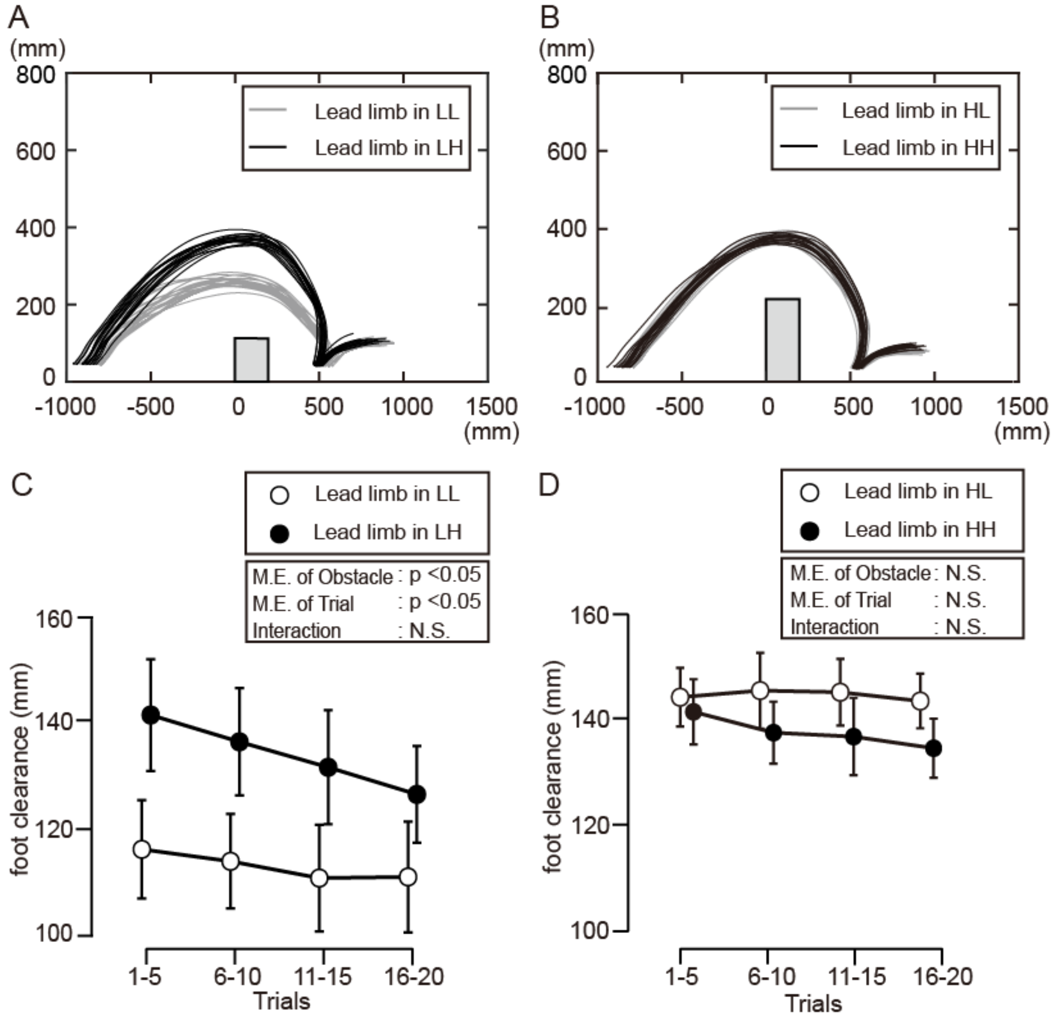

Figure 3-4. Measurements of the foot clearance with the lead limb. A, B: The trajectories of the marker attached to the head of the first metatarsal of the lead foot for one participant are superimposed. The gray box indicates the obstacle. C, D: The mean values of all subjects and 95% confidence intervals of the clearance.

	Lead limb in condition LL				Lead limb in condition LH				M.E. of Obstacle			M.E. of Trial			Interaction		
	Trials 1-5	6-10	11-15	16-20	Trials 1-5	6-10	11-15	16-20	F	p	η^2	F	p	η^2	F	p	η^2
Foot clearance	116 ± 22	114 ± 21	111 ± 18	111 ± 19	142 ± 36	137 ± 37	132 ± 37	127 ± 35	7.43	0.02	0.33	5.75	0.00	0.28	2.23	0.10	0.13
Horizontal distance before obstacle	770 ± 82	773 ± 74	768 ± 67	767 ± 80	744 ± 97	762 ± 77	782 ± 92	792 ± 85	0.00	0.95	0.00	3.36	0.03	0.18	6.31	0.00	0.30
Horizontal distance after obstacle	334 ± 42	331 ± 36	327 ± 35	333 ± 34	309 ± 30	309 ± 32	305 ± 39	300 ± 38	10.1	0.01	0.40	1.34	0.27	0.08	1.30	0.29	0.08
	Lead limb in condition HL				Lead limb in condition HH				M.E. of Obstacle			M.E. of Trial			Interaction		
	Trials 1-5	6-10	11-15	16-20	Trials 1-5	6-10	11-15	16-20	F	p	η^2	F	p	η^2	F	p	η^2
Foot clearance	143 ± 35	144 ± 38	144 ± 39	142 ± 34	141 ± 30	137 ± 30	137 ± 32	135 ± 31	3.55	0.08	0.19	0.99	0.41	0.06	0.76	0.52	0.05
Horizontal distance before obstacle	741 ± 81	746 ± 78	750 ± 80	754 ± 64	756 ± 90	761 ± 78	771 ± 74	764 ± 89	3.60	0.08	0.19	0.48	0.70	0.03	0.21	0.89	0.01
Horizontal distance after obstacle	357 ± 31	355 ± 36	354 ± 37	355 ± 36	340 ± 29	341 ± 24	338 ± 24	337 ± 26	15.3	0.00	0.50	0.27	0.85	0.02	0.14	0.93	0.01
	Trail limb in condition LL				Trail limb in condition HL				M.E. of Obstacle			M.E. of Trial			Interaction		
	Trials 1-5	6-10	11-15	16-20	Trials 1-5	6-10	11-15	16-20	F	p	η^2	F	p	η^2	F	p	η^2
Foot clearance	90 ± 26	87 ± 32	88 ± 27	85 ± 32	122 ± 47	112 ± 45	108 ± 41	101 ± 35	5.18	0.04	0.26	4.38	0.01	0.23	1.90	0.14	0.11
Horizontal distance before obstacle	156 ± 35	156 ± 30	156 ± 32	156 ± 33	143 ± 33	143 ± 28	141 ± 30	136 ± 24	8.02	0.01	0.35	0.43	0.74	0.03	0.39	0.76	0.03
Horizontal distance after obstacle	957 ± 65	962 ± 68	958 ± 64	966 ± 61	962 ± 72	967 ± 79	972 ± 64	977 ± 59	0.42	0.53	0.03	1.52	0.22	0.09	0.30	0.82	0.02
	Trial limb in condition LH				Trail limb in condition HH				M.E. of Obstacle			M.E. of Trial			Interaction		
	Trials 1-5	6-10	11-15	16-20	Trials 1-5	6-10	11-15	16-20	F	p	η^2	F	p	η^2	F	p	η^2
Foot clearance	159 ± 60	146 ± 72	133 ± 57	125 ± 58	137 ± 54	131 ± 50	127 ± 43	121 ± 50	1.38	0.26	0.08	9.77	< .001	0.39	1.04	0.38	0.07
Horizontal distance before obstacle	170 ± 38	168 ± 38	178 ± 39	182 ± 44	164 ± 34	157 ± 31	162 ± 30	158 ± 33	3.97	0.07	0.21	1.65	0.19	0.10	3.33	0.03	0.18
Horizontal distance after obstacle	923 ± 65	934 ± 75	935 ± 80	926 ± 64	946 ± 86	952 ± 78	953 ± 79	949 ± 73	2.49	0.14	0.14	1.05	0.38	0.07	0.10	0.96	0.01

Table 3-1. Descriptives statistics and ANOVA of the foot clearance, prestep distance, and poststep distance.

Discussion

In this study, we compared the clearance of the lead and trail legs when crossing over side-by-side obstacles of unequal heights. We observed that the foot trajectory when crossing obstacles were affected not only by the height of the obstacle to be crossed but also by the contralateral obstacle in which the preceding or the following step was made. An interesting feature of the results was the asymmetry of the effect of the contralateral obstacle: the lead limb clearance over the low obstacle was larger when the trail obstacle was high (LH condition) and it was smaller when the trail obstacle was low (LL condition), whereas the lead limb clearance over the high obstacle was not influenced by the contralateral obstacle's height (no difference between the HL and HH conditions). A similar effect was also observed in the trailing limb. Since foot clearance is the safety margin in the obstacle-crossing task, decreasing the clearance might lead to a higher risk of tripping. The observed asymmetric effect of the contralateral obstacle on foot clearance might be explained by the safety-first principle of gait and posture motor control: the primary goal of gait and posture control is to avoid falls and fatal fall-related injuries [4]. Psychological studies have suggested that affordance for adaptive locomotor tasks such as stair climbing and obstacle crossing is established not only by using the information of the object itself (i.e., stair or obstacle) but also by integrating various information such as the surrounding environment and the subject's motor capabilities [66,67]. Our result might reflect the comprehensive information processing that takes place to control gait and posture safely.

The result that the trajectory of the lead limb was affected by the height of the trail obstacle was not explained by the sequential interlimb interaction, but it suggests the predictive motor control based on the given environment. Motor adaptation experiments have suggested that the same arm-reaching movement might be represented in different ways in the motor system depending on contextual factors such as the movement of the other limb or movements performed immediately before or after the focal reaching movement. Nozaki et al. (2006) [28] demonstrated that learning a novel load during unimanual reaching is partially but not completely transferred to the same limb during bimanual reaching. They also reported that the learned dynamics were revealed only by the original context (i.e., unimanual or bimanual) and found that subjects could learn two conflicting force fields if one were associated with unimanual and the other with bimanual reaching. Howard and his colleagues demonstrated that different lead-in or follow-through movements accompanied by a kinematically identical arm-reaching movement formed different motor representations of the same arm-reaching movement [29,30]. Hagio et al. (2020) [32] revealed that visuomotor processing was shared between lead and trail limbs in their motor learning experiment using obstacle-crossing tasks in a VR environment.

Based upon the above studies, we discuss that the central nervous system processes the visual information of the given environmental context including obstacles with different heights, and controls the foot clearance of the lead and trail limbs to negotiate the obstacles. The results of the prestep and poststep distances also suggest that the lead and trail limbs are not controlled independently but comprehensively. The prestep distance of the trail (left) limb was longer in the LL condition than in the HL condition. The result means that the participants placed the left foot far away from the obstacle when the right leg was to cross the low obstacle and placed the left foot close to the obstacle when the right leg was to cross the high obstacle. The consistent results were observed in the poststep distance of the lead (right) limb in the comparison between the LL and LH conditions and between the HL and HH conditions. Pearson et al. (2015) [68] reported the anteroposterior hip-to-toe distance was biomechanically related to the toe trajectory slope: a long hip-to-toe distance would yield a shallow slope, and a short distance would yield a steep slope. The participants in this study might take into account the control of the contralateral limb to determine the anteroposterior foot placements.

Although we analyzed only the foot trajectories in this paper, the foot trajectory of the swing limb results from the coordination of multiple joints, including joints in the support limb, trunk, and swing limb. In the comparison between HL and LL conditions, for example, the difference in the height of the obstacle for the lead limb might influence the position and velocity of the hip at the takeoff of the trailing limb to cross the low obstacle. Different swing durations owing to different obstacle heights could also affect the state of the body. For example, the swing duration of the lead limb would be longer in the HL condition than in the LL condition because the obstacle on the lead limb side was higher. The elongation could affect the positions and velocities of the hip and trunk. Biomechanically detailed measurements and analyses would be required to investigate such questions.

It would also be interesting to study the behavior of older people in a similar obstacle-crossing task, where the lead and trail limbs cross obstacles of different heights. Many studies have reported physical and cognitive deficiencies in elderly people such as reduced muscle strength, reduced joint flexibility, and impaired working memory [13,31,47]. Recent studies have reported that even healthy older adults are unaware of their age-related physical decline and have difficulty in appropriately gauging the relationship between their physical ability and their environment [26,69].

Cognitively impaired older adults showed lower trailing limb clearance and thus greater foot clearance asymmetries than young adults [70]. This is because, due to its invisible movement, stepping over an obstacle with the trailing limb is mostly guided by the working memory of the obstacle height [71]. Obstacles in daily living are not always symmetrically or regularly shaped. Our results revealed the comprehensive interlimb motor control for negotiating such a complex environment, suggesting that studies using a simple obstacle might not be sufficient to assess the real-life risks in adaptive locomotion. Although this study only used healthy young volunteers, studies on people with a large asymmetry and/or cognitive impairments, such as the elderly population, stroke survivors, and Parkinson's disease, would shed light on how physical and cognitive decline affects obstacle crossing in the complex environment.

Conclusions

In conclusion, the trajectory of a limb in crossing over an obstacle was affected not only by the height of the obstacle to be crossed but also by the obstacle on the other side. This suggests that there is an interaction between the lead and trail limbs in the motor control system. And also, It is expected that research on people with a high asymmetry of leading and trailing limb movements in obstacle avoidance gait, such as

Parkinson's disease patients [51]. It would be interesting for future studies to take this into account and investigate how the foot trajectory is controlled for fall prevention in the elderly.

Funding

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Chapter 4.
The shape of the obstacle affects the left-right trajectory of the lower limb when stepping over the obstacle
(Experiment 2)

Abstract

In previous studies of crossing over obstacles, vertical foot clearance has been used as an indicator of the risk of contact. Under normal circumstances, people do not always step over obstacles of the same height on both sides, and depending on the shape of the obstacle, the risk of contact may differ depending on the foot elevation position. Therefore, the objective of this investigation is to determine the influence of the shape of an obstacle on the positioning of the foot. Sixteen healthy young adults performed a task in which they crossed over two obstacles with different shapes: a trapezoidal obstacle and a rectangular obstacle, as viewed from the frontal plane while walking. The results showed that when crossing over a trapezoidal obstacle, the participants-maintained foot clearance by controlling the mediolateral direction, which reduced the height of the obstacle. The results of this study suggest that lower limb movements during walking over an obstacle are controlled not only in the vertical direction but also in the mediolateral direction by controlling the foot trajectory to reduce the risk of contact. It was demonstrated that the control was comprehensive, considering the shape of the obstacle, including the opposite limb.

Yuka Miura, Kohei Yoshimoto, Masahiro Shinya, The shape of the obstacle affects the left-right trajectory of the lower limb when stepping over the obstacle, Frontiers in Sports and Active Living (under review).

Chapter 4.
The shape of the obstacle affects the left-right trajectory of the lower limb when stepping over the obstacle
(Experiment 2)

Abstract (in Japanese)

これまでの障害物跨ぎ越し歩行研究では、鉛直方向のクリアランスを障害物との接触リスクの指標として用いてきた。日常生活では必ずしも左右で一様な高さの障害物を跨ぐとは限らず、障害物の形状によっては足部の挙上位置に応じて、障害物との接触リスクが異なる可能性がある。そこで本研究では、障害物の形状によって足部がどのように制御されているかを明らかにすることを目的とした。健常な若年成人16名を対象に、歩行中に前額面から見て台形の障害物と長方形の障害物の 2 つの形状の障害物を跨ぐ課題を実施した。その結果、台形の障害物を跨ぐ際は、障害物の高さが低くなる左右方向の制御を行うことでクリアランスを確保していることが示された。本研究の結果から、障害物跨ぎ越し歩行における下肢の運動は、鉛直方向だけではなく左右方向の足部軌跡の制御を行うことで、接触リスクを下げる戦略を行い、反対脚も含めた障害物全体の形状を考慮に入れた包括的な制御を行っていることが示唆された。

Yuka Miura, Kohei Yoshimoto, Masahiro Shinya, The shape of the obstacle affects the left-right trajectory of the lower limb when stepping over the obstacle, Frontiers in Sports and Active Living (under review).

Introduction

Falls can have a deleterious effect on health, independence, and quality of life across all ages [72]. One of the causes of falling is contact with obstacles [60,61,72,73]. To predict and prevent falls, scientists have investigated the foot trajectory during obstacle traversal [10]. In previous obstacle-crossing studies, the vertical foot clearance i.e., the vertical distance between the foot and an obstacle, has been used as a main kinematic outcome [10,16,51,74,75]. Clearance has been used to assess the risk of contact between obstacles and the foot. It was revealed that the clearance was affected by the risk of falling [27], and the effects of aging [16]. Clearance during the traversal of obstacles has also been used as an indicator of improvement in adaptive walking ability in stroke patients [76]. Based on these findings, clearance is often used in clinical practice as a measure of walking ability associated with certain diseases or aging.

It is known that foot clearance depends on the obstacle's properties such as height and location. However, it has also been shown that clearance is influenced by the environment in which walking is performed. Clearance increases with the height of the obstacle, and also, it was clear that the clearance was greater when the pattern of the obstacle to be crossed was vertical compared to a horizontal pattern [7]. In addition, the color contrast of obstacles was another factor that impacted clearance, and it has been reported that the high contrast of the colors black and white also resulted in greater clearance [8]. Heijnen et al. (2012) [12] found that clearance decreased during repeated obstacle-crossing tasks.

The results of previous research suggest that foot clearance was determined based on the tradeoff between energy consumption to control the lower limb and the risk of contact with an obstacle. Although the basic principle of motor control is energy minimization [12], a zero-clearance trajectory is not optimal considering inherent sensorimotor noise and the risk of contact with obstacles. Instead, the central nervous system plans the trajectory of the foot to maintain a certain clearance as a safety margin. For example, Shinya et al. (2012) [13] reported that stair-climbing tasks resulted in higher clearance under conditions in which the memory of stair height was obscured by averted gaze. Most previous studies focused on the foot trajectory in the sagittal plane (i.e., vertical foot clearance), however, the influence of obstacle traversal on the mediolateral foot position during walking should also be investigated.

Lower limb movements in obstacle crossing were controlled based on energy minimization strategies [12], and Slawinski et al. (2012) [77] reported that in healthy participants, the more the foot was elevated, the greater the energy expenditure. Although there are no studies that quantitatively estimate the energy expenditure associated with the vertical MP1 position during obstacle crossing, the results presented to date suggest that this position is more efficient in the lateral direction compared to the vertical direction in achieving the same amount of foot clearance. Although the risk of contact with the obstacle and energy consumption must be considered in obstacle-crossing, postural stability must also be considered. Yamagata et al. (2021) [78] reported that excessive foot elevation in obstacle-crossing would induce postural instability in the mediolateral direction. Accordingly, a safer strategy for the crossing of irregularly shaped obstacles should be adopted, such as increasing the MP1 position in the mediolateral direction to reduce the risk of contact with the obstacle, instead of reducing the risk of contact by elevating the foot.

In previous studies, since the obstacle height was the same in the mediolateral direction, the foot clearance and the risk of collision would not change with the mediolateral foot movement. In this case, the control of the foot position is relevant only in the vertical direction. In contrast, if an obstacle is trapezoidal in the frontal plane and the top edge is tilted in the mediolateral direction, the mediolateral foot position would be task-relevant. For instance, if the top edge of an obstacle is right-up-left-down, moving the foot leftward would increase the clearance even if the vertical elevation is the same. As such, it is not clear if the mediolateral foot position is influenced during obstacle crossing. In this study, we used trapezoidal obstacles, of which the top edge was not flat but tilted in the frontal plane, as well as a rectangular obstacle (Figure 4-1). Since the foot was moved in the mediolateral direction, it was expected that the radial clearance between the foot and the trapezoidal obstacles would be maintained.

Methods

Participants

The inclusion criteria for participants of the study included the absence of impediments to normal locomotion and the requirement of normal or corrected-to-normal vision. As exclusion criteria, the participants must not have neurological or musculoskeletal disorders. An a priori power analysis was performed based on repeated ANOVA tests using G*power 3.1.9.7. The parameters for the power analysis were set as follows: effect size f = 0.30, alpha = 0.05, 1-beta = 0.8, number of groups = 1, number of measurements = 7, correlation among measures = 0.50, and non-sphericity correction e = 1. The effect size f was obtained from the vertical clearance observed in our previous report [79]. The suggested sample size was twelve. Conservatively, we recruited sixteen healthy young volunteers (eight males/eight females; age: 21.3 ± 1.7 years; height: 165.6 ± 7.9 cm; weight: 59.6 ± 9.9 kg, mean ± standard deviation). All subjects gave written informed consent before participation, and the ethics committee of the Graduate School of Integrated Arts and Sciences, Hiroshima University, approved the study (approval number: 02-30) according to the Declaration of Helsinki.

Experimental protocol

Each volunteer walked at a self-selected pace on a 7 m walkway and stepped over an obstacle. The volunteers were instructed to walk upright and step over the obstacle with the right (leading) limb in the seventh step and the left (trailing) limb in the eighth step. An obstacle was placed in the middle of the walkway. Before the recording session, the volunteers were instructed to adjust the starting position without stepping over the obstacle. We used rectangular and trapezoidal obstacles as illustrated in Figure 4-1. The height of the rectangular obstacle was 15 cm. Since both the leading limb and trailing limb were expected to cross the height of 15 cm, we referred to the rectangular obstacle as L15-T15. In one group of the trapezoidal obstacles, the height at 10 cm to the right of the middle of the obstacle was fixed to 15 cm, and the height at 10 cm to the left of the middle of the obstacle was set to 10, 12, 14, 16, 18, and 20 cm (Figure 4-1-B). We referred to these trapezoidal obstacles as L15-T10, L15-T12, L15-T14, L15-T16, L15-T18, and L15-T20, respectively. Similarly, we created another group of trapezoidal obstacles (L10-T15, L12-T15, L14-T15, L16-T15, L18-T15, and L20-T15) of which the height at 10 cm to the left was fixed to 15 cm, and the height at 10 cm to the right was set to 10, 12, 14, 16, 18, and 20 cm (Figure 4-1-C).

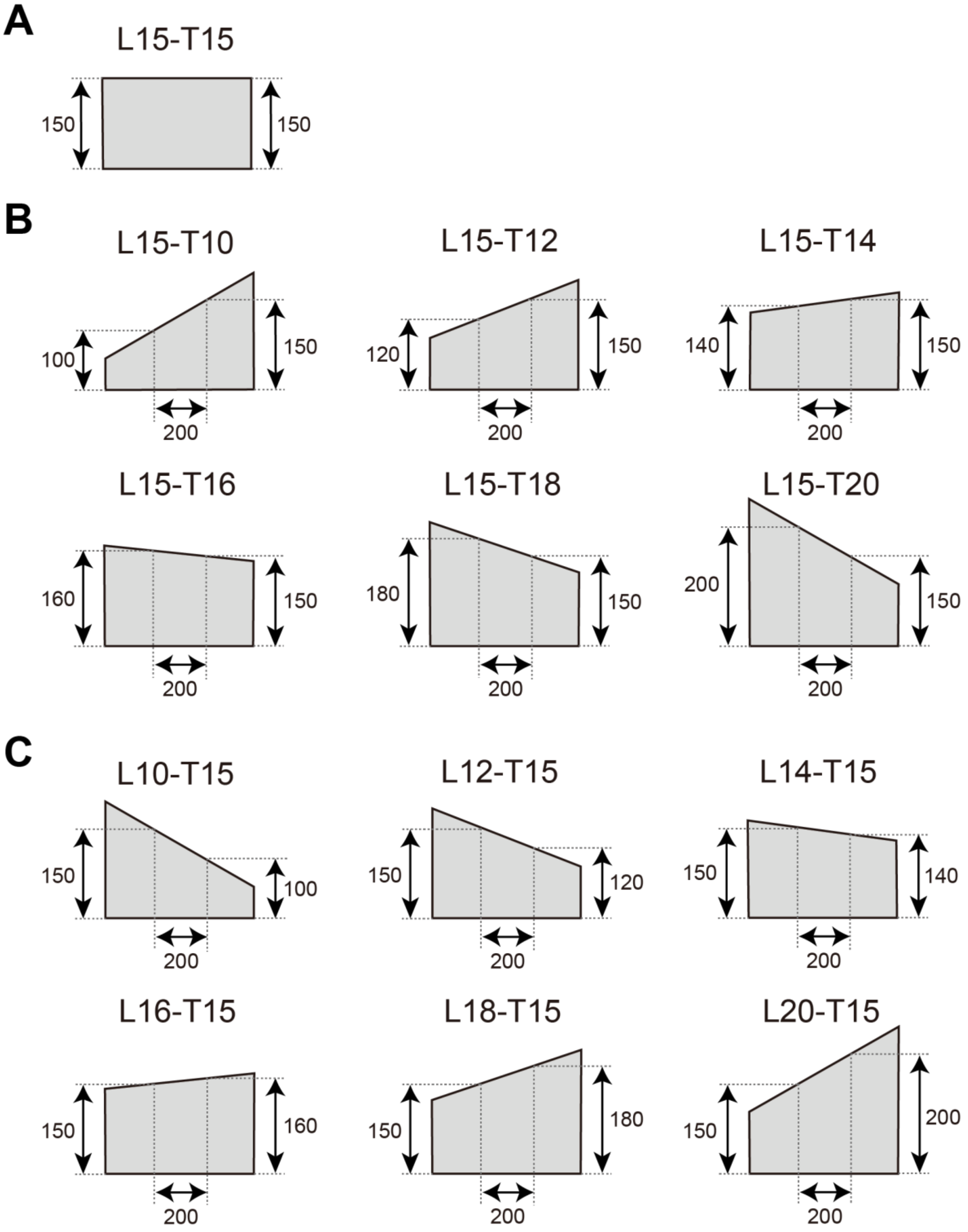

Figure 4-1. The geometry of the obstacles. A. A rectangular 150-mm-height obstacle with a flat top edge was used as a reference. B. Trapezoidal obstacles of which the height of the leading limb was fixed at 150 mm. The height of the trailing limb was set from 100

mm to 200 mm. C. Trapezoidal obstacles of which the height of the trailing limb was fixed at 150 mm.

The experiment was block-designed. The participants repeated ten trials for a given obstacle session and then moved to another obstacle session. The order of the session varied among the participants. Sessions 1, 8, and 15 were always the rectangular obstacle (15-15) sessions. For eight participants, sessions 2–7 were group B trapezoidal obstacles (15–**), and sessions 9–14 were group C obstacles (**-15). For the other eight participants, the order of group B and C trapezoidal obstacles was opposite. Within sessions 2–7 or 9–14, the order of the obstacles was randomized so that right-side-down and left-side-down obstacles were alternated.

Data collection

Reflective markers were pasted on two anatomical landmarks on the left and right distal condyle of the first metatarsal bone. The markers were captured using a 3D optical motion caption system (Qualisys Track Manager, Qualisys, Göteborg, Sweden) with eight cameras (Qualisys-Miqus M3, Qualisys). The sampling frequency of the kinematic data was 250 Hz. The measured signals were stored on a computer, and all numerical calculations were performed using MATLAB 2017b (Math Works, Inc., MA, USA).

Data analysis

In this study, participants were not asked to practice crossing over before the experiment. Therefore, the first ten trials in which participants traversed a rectangular obstacle were excluded from the analysis. In addition, the left leg was the leading limb in two trials. The left toe marker could not be measured because it could not be captured by the camera in two trials. The participants contacted the obstacle in ten trials. These trials were excluded from the analysis. The kinematic data were low-pass filtered using a zero-lag second-order Butterworth digital filter with a cutoff frequency of 10 Hz. The limb trajectory during obstacle crossing was quantified for the leading and trailing limbs using the following parameters (Figure 4-2). The vertical MP1 position was defined as being measured from the floor. The mediolateral MP1 position was in the mediolateral direction with the center of the obstacle as the origin. The MP1 radial clearance was the shortest distance from the obstacle to the MP1 marker and the MP5 radial clearance was the shortest distance from the obstacle to the MP5 marker.

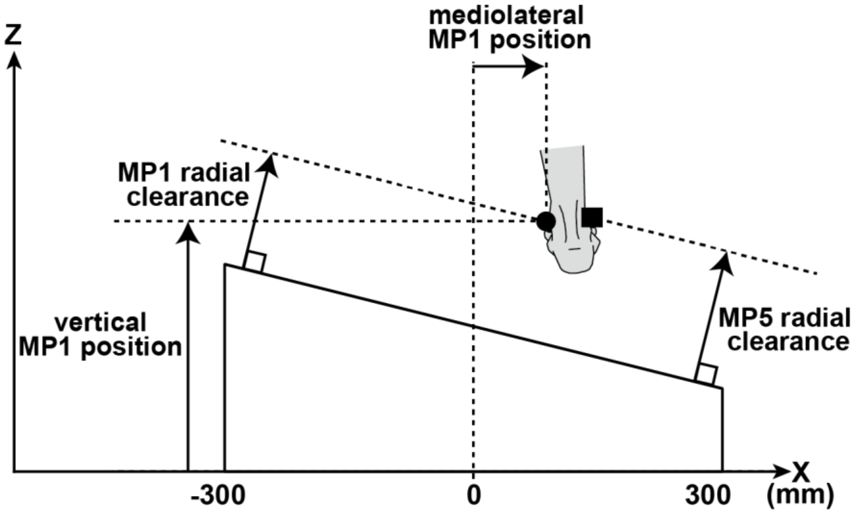

Figure 4-2. Illustration of radial foot clearances in the frontal plane. The foot clearances were calculated based on MP1 (black circle) and MP5 (black square) markers.

Statistics

For all the dependent variables, we used one-way repeated-measures ANOVA to investigate the effect of the obstacle's shape on the foot trajectory of the lower limb. Bonferroni correction was used for the post hoc comparisons. If a violation of sphericity was determined using Mauchly's Test, Greenhouse–Geisser correction was performed. The significance was set a priori at $p < 0.05$. Statistical analyses were performed using JASP version 0.16.1.0 (Eric-Jan Wagenmakers, Amsterdam, Netherlands).

Results

In this study, the lower limb movements during the traversal of an obstacle were controlled not only in the vertical direction but also in the mediolateral direction by controlling the foot trajectory to reduce the risk of contact. The results for the vertical MP1 position, mediolateral MP1 position, and MP1 and MP5 radial clearance are presented in the following section.

Repeated measures ANOVA tests revealed the significant influential effects of the obstacle conditions on the vertical MP1 position in the leading and trailing limbs. (leading limb: $F_{(2.804,42.065)} = 3.823, p = 0.018, \eta^2 = 0.203$; trailing limb: $F_{(6, 90)} = 6.363, p < .001, \eta^2 = 0.298$). Based on the post hoc test, the vertical MP1 position of the leading limb in the L15-T10 and L15-T12 was larger compared to that of the rectangular obstacle (i.e., L15-T15). (L15-T10 :$t\ (15) = 3.669, p < 0.0083$, *Cohen's* $d = 0.374$; L15-T12 : $t\ (15) = 3.38, p < 0.0083$, *Cohen's* $d = 0.345$) (Figure 4-3-B). The vertical MP1 position of the trailing limb in the L10-T15 was larger than that of the rectangular obstacle (L10-T15: $t\ (15) = 5.377, p < 0.0083$, *Cohen's* $d = 0.672$) (Figure 4-3-D).

Significant influential effects of the obstacle conditions on the mediolateral MP1 position were observed for the leading and trailing limbs (leading limb: $F_{(2.436, 36.535)} = 18.244, p < .001, \eta^2 = 0.549$; trailing limb: $F_{(1.866, 27.997)} = 20.301, p < .001, \eta^2 = 0.575$). There were significant differences between L15-T12 and L15-T15, between L15-T20 and L15-T15 in the leading limb (L15-T12: t $(15) = -3.341, p < 0.0083$, *Cohen's* $d = -0.591$;

L15-T20: *t (15) = -4.814, p < 0.0083, Cohen's d = -0.852*) (Figure 4-3-B). There were significant differences between L10-T15 and L15-T15, between L12-T15 and L15-T15, and between L20-T15 and L15-T15 in the trailing limb (L10-T15: *t(15) = 4.554, p < 0.0083, Cohen's d = 0.683*; L12-T15: *t(15) = 3.767, p < 0.0083, Cohen's d = 0.565*; L20-T15: *t(15) = 3.467, p < 0.0083, Cohen's d = 0.52*) (Figure 4-3-D). These results indicate that both the leading and trailing limbs were consistently displaced in the direction of the low height of the obstacle during the crossing of the trapezoidal obstacles.

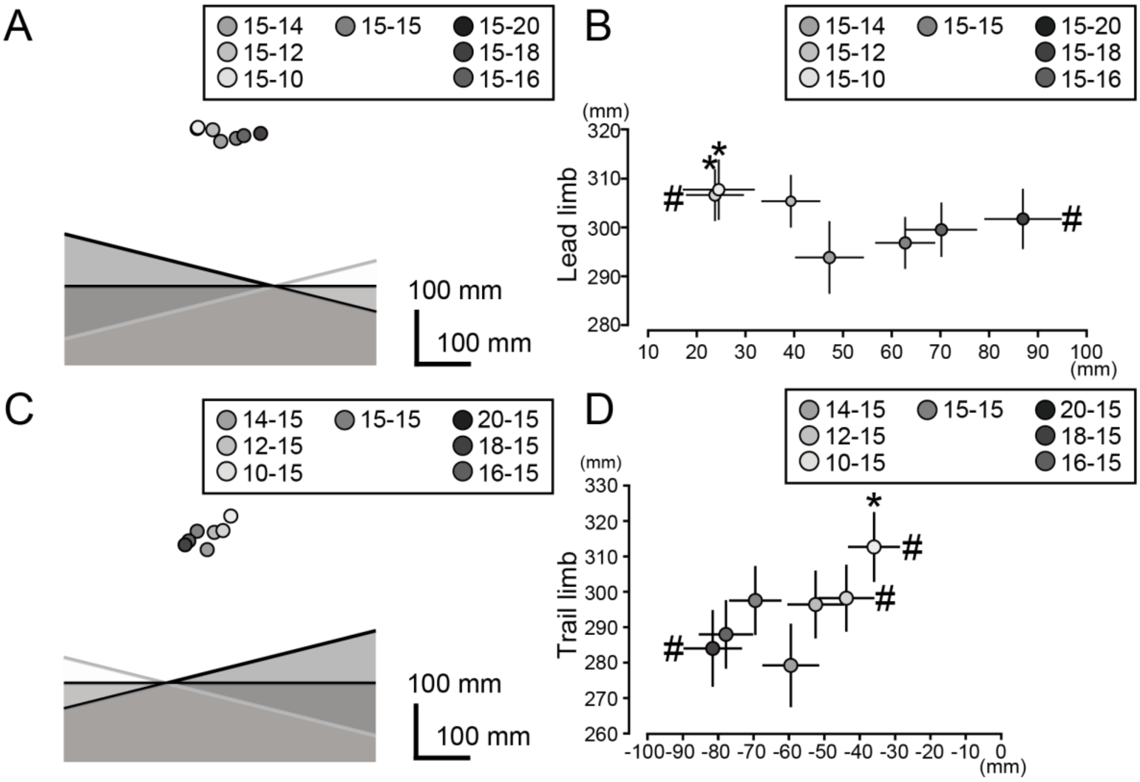

Figure 4-3. The vertical and mediolateral MP1 position of the leading limb (A, B) and trailing limb (C, D). In the left panels, the mean MP1 positions for all the obstacle

conditions are shown. To visualize the foot position relative to the obstacle, three obstacles (15-10, 15-15, and 15-20 in panel A; 10-15, 15-15, and 20-15 in panel C) are illustrated in panels A and C. The right panels show the mean and standard deviations of the foot position (B, D). The asterisks and hash marks indicate significant differences for the rectangular 15-15 obstacles in the vertical and mediolateral MP1 positions, respectively. The significance level was adjusted to $p < 0.0083$ *(0.05/6)* based on the Bonferroni correction.

Significant influential effects of the obstacle's conditions on the MP1 radial clearance were observed in the leading and trailing limbs (leading limb: $F_{(6, 90)} = 21.948, p < .001, \eta^2 = 0.594$; trailing limb: $F_{(6, 90)} = 15.607, p < .001, \eta^2 = 0.510$). A significantly larger MP1 radial clearance was observed in the L15-T10, L15-T12, and L15-T14 compared to that of the rectangular obstacle in the leading limb (L15-T10: $t(15) = 8.248, p < 0.0083$, *Cohen's* $d = 0.808$; L15-T12: $t(15) = 6.61, p < 0.0083$, *Cohen's* $d = 0.648$; L15-T14: $t(15) = 4.45, p < 0.0083$, *Cohen's* $d = 0.436$) (Figure 4-4-A), and L10-T15, L12-T15 and L14-T15 compared to that of the rectangular obstacle in the trailing limb (L10-T15: $t(15) = 7.843, p < 0.0083$, *Cohen's* $d = 0.961$; L12-T15: $t(15) = 4.6, p < 0.0083$, *Cohen's* $d = 0.564$; L14-T15: $t(15) = 3.64, p < 0.0083$, *Cohen's* $d = 0.446$)

(Figure 4-4-B).

There was a significant influential effect of the obstacle conditions on the MP5 radial clearance in the leading and trailing limbs (leading limb: $F_{(6, 90)} = 7.259, p < .001, \eta^2 = 0.326$; trailing limb: $F_{(6, 90)} = 4.071, p = 0.001, \eta^2 = 0.213$). A significantly larger MP5 radial clearance was observed in the L15-T18 and L15-T20 compared to that of the rectangular obstacle in the leading limb (L15-T18: $t(15) = -3.977, p < 0.0083$, *Cohen's d* $= -0.437$; L15-T20: $t(15) = -6.261, p < 0.0083$, *Cohen's d* $= -0.688$) (Figure 4-4-A). A significantly larger MP5 radial clearance was observed in the L10-T15 and L16-T15 compared to that of the rectangular obstacle in the trailing limb (L10-T15: $t(15) = 4.508, p < 0.0083$, *Cohen's d* $= 0.58$; L16-T15: $t(15) = -3.931, p < 0.0083$, *Cohen's d* $= -0.505$) (Figure 4-4-B).

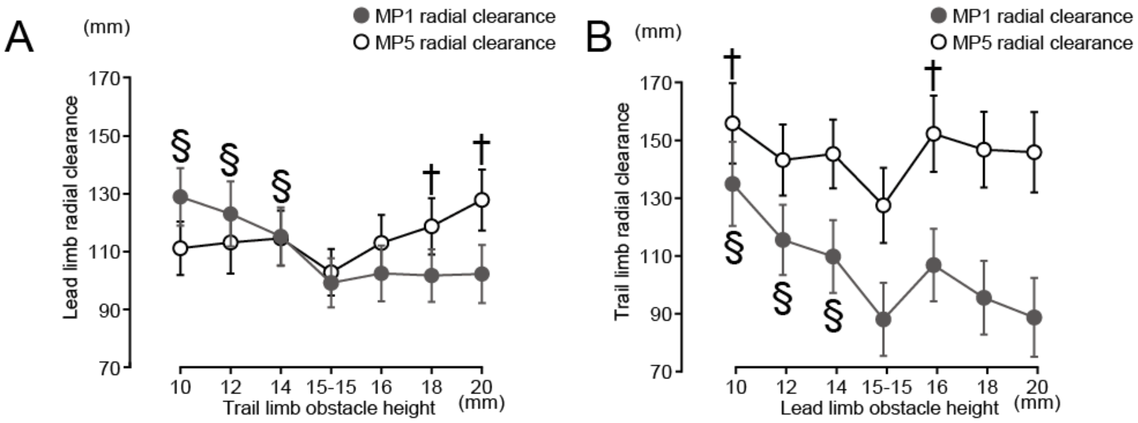

Figure 4-4. The MP1 and MP5 radial clearance of the leading limb (A) and trailing limb

(B). The mean and the 95% confidence intervals are illustrated. The daggers indicate significant differences for the rectangular obstacle (150 mm condition) in MP1 radial clearance with $p < 0.0083$ *(0.05/6)*. The section describes the significant differences for the rectangular obstacle (150 mm condition) in the case of MP5 radial clearance with $p < 0.0083$ *(0.05/6)*.

Discussion

We intended to investigate whether the mediolateral foot position was task-influenced during obstacle crossing. In the investigation, the foot trajectory during the crossing of trapezoidal obstacles was measured. The hypothesis was confirmed based on the results that if the obstacle was left-up-right-down, the foot was moved rightward compared to the flat obstacle condition and vice versa for the right-up-left-down obstacles. The amplitude of the mediolateral MP1 position was linearly related to the tilt angle of the obstacle. The foot trajectory for obstacle crossing was determined by considering the tradeoff between energy minimization and the minimization of the risk of contact with obstacles [12]. The physiological energy increases in proportion to the lifting height in obstacle-crossing [77]. Although no studies have quantitatively estimated the energy expenditure associated with the mediolateral MP1 position during obstacle traversal, it is possible that at least for our healthy young participants, the mediolateral MP1 position might be more efficient than vertically lifting the foot to ensure foot clearance. The observed mediolateral movement of the foot might be regarded as a strategy for securing clearance when traversing trapezoidal obstacles.

For the leading limb, a significantly larger MP1 radial clearance was observed when the participants crossed the L15-T10, L15-T12, and L15-T14 trapezoidal obstacles compared to the 15-cm-high rectangular obstacle. For these obstacles, the lateral side was higher than the medial side resulting in an increased risk of contact of the lateral side of the foot with the obstacles. For these obstacle conditions, the radial clearance that was determined using the MP5 marker was not significantly different from the rectangular obstacle condition. Conversely, the MP1 radial clearance for the L15-T16, L15-T18, and L15-T20 obstacles was not significantly different from that of the rectangular obstacle, whereas the MP5 radial clearance for the L15-T18 and L15-T20 obstacles was larger compared to that of the rectangular obstacle. Overall, the smaller value for the radial clearances of MP1 and MP5 in any trapezoidal obstacle was not statistically different from the foot clearance in the rectangular obstacle. A similar result was also confirmed for the trailing limb. These findings suggest that the participants-maintained foot clearance and the risk of collision of both the medial and lateral sides of the foot with the obstacles.

As previously indicated, the foot clearance for the trapezoidal obstacles was not significantly different from that for the rectangular obstacle. The only exception was the L10-T15 condition where both the MP1 and MP5 radial clearances for the trailing limb were larger compared to that of the reference foot clearance for the rectangular obstacle. The traversal of obstacles while walking is dependent on the visual information stored in the brain [4]. The position of the trailing limb relative to an obstacle cannot be confirmed using online visual information. This means that the control of the trailing limb is more uncertain compared to the leading limb. Previous studies have reported an increase in foot clearance in the case of high uncertainty, such as when the subject's gaze was averted from the stair for 2 seconds or more [13]. In the L10-T15 condition, the obstacle's height was higher on the lateral side of the trailing limb, where the risk of collision could be higher for the lateral side of the foot. A previous psychological study demonstrated that humans tend to misjudge their foot position as being more medial compared to their actual foot position and the authors suggested that this discrepancy might lead to unexpected tripping during walking [22]. If the perception of the location of the lateral side of the foot is uncertain, the results indicate that the participants increase foot clearance when the risk of tripping is considered as a security strategy for adaptive locomotion.

Although the result of the present study was qualitatively reasonable, it might be premature to conclude that it is optimal in a quantitative sense. The basic principle of motor control is energy minimization [12]. If it applies to our experimental results, the observed mediolateral MP1 position can be regarded as an energy-efficient strategy to ensure foot clearance compared to the vertical MP1 position, which guarantees the same clearance. For the shallowest conditions, the slope of the top edge of the obstacle was only 5% (i.e., 1 cm vertical difference for 20 cm width). For such obstacles, we observed approximately 1 cm mediolateral displacement, which contributes to an increase of the clearance by 0.5 mm. In these cases, the energy cost of moving the foot 1 cm along a mediolateral trajectory should be comparable to that associated with vertically lifting the foot by 0.5 mm. When we examined the steepest condition for which the slope was 25%, the observed mediolateral MP1 positions were 2–3 cm. The proportion of the observed mediolateral MP1 position and the slope was not linear for the various tested slopes. Detailed computational studies are required to determine whether the observed mediolateral displacements are quantitatively equivalent in terms of securing foot clearance.

It is known that human decision-making might be suboptimal in economic, perceptual, and motor tasks [80,81]. Ota and his colleagues reported on persistent suboptimality in decision-making when the cost function was asymmetric for the given task [82–84]. In his study, the subjects were rewarded as their performance improved to be close to the target. However, zero rewards were given if the performance exceeded the target. They considered that the non-linearity of the cost function might be a challenge in terms of calculating the optimal solution. Obstacle-crossing tasks have a similar cost function wherein the physiological cost gradually decreases as the clearance becomes close to zero. However, a high cost would be associated with tripping if the clearance is negative. Although we did not test the optimality of the obstacle-crossing behavior, it should be noted that the non-linearity of the cost function in obstacle-crossing tasks may limit the motor control system in terms of quantitatively calculating the optimal obstacle-crossing behavior.

It would be interesting to investigate the foot trajectory in the frontal plane of elderly people, amputees, and patients diagnosed with stroke or Parkinson's disease. For these populations, it can be assumed that the motor cost of lifting the foot was higher, the balance-maintaining ability was lower, the result of the tripping was more serious, and perception and memory-related functions were impaired compared to healthy young people [26,51,85]. Crossing a trapezoidal obstacle is a complex task that requires the integration of these functions. Ambulatory obstacle-crossing has been reported to be different in patients with Parkinson's disease compared to healthy individuals, with increased asymmetry in the left and right legs [51] and greater clearance in stroke patients [86]. These findings suggest that the behavior of trapezoidal obstacle crossing in other populations (e.g., osteoarthritis patients, hemiplegic patients, and individuals with other musculoskeletal and neurological disorders) may differ compared to healthy subjects. In future research, the crossing over-straddle behavior in other populations with different locomotor costs for healthy individuals to determine how the disease may affect obstacle crossing in complex environments.

Conclusions

In this study, we observed that the leading limb moved the foot to the left when the obstacle shape was upper right and lower left, and conversely, moved the foot to the right when the obstacle shape was lower right and upper left. The same behavior was observed in the trailing limb as in the leading limb. These results suggest that the mediolateral position of the feet when crossing over obstacles is influenced by the shape of the obstacle. In addition, in the leading limb radial clearance, MP5 radial clearance maintained the same clearance as a rectangular obstacle when the shape was upper right and lower left. Conversely, when the obstacle’s shape was lower right and upper left, the

MP1 radial clearance maintained the same clearance as a rectangular obstacle. The same behavior was generally observed in the trailing limb. These results suggest that the participants-maintained foot clearance and both the medial and lateral sides of the foot were at risk of collision with the obstacle.

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Chapter 5.
General Discussion

Abstract

The objective of this study was to determine whether the trajectory of the foot during obstacle crossing is differentially controlled by the shape of the obstacle. The main findings are as follows: (1) There was an interaction in the motor control between the leading and trailing limbs, and the height of the obstacle crossed by the opposite leg and the motion of the opposite leg affected the motor control of the lower limb during the traversal of the obstacle. (2) When crossing an irregularly shaped obstacle, the motion of the lower limb was controlled not only in the vertical direction but also in the lateral direction, considering the shape of the obstacle. (3) This implies that even a healthy person may perform irrational crossing-over movements. (4) The motion of the lower limb in crossing obstacles is not determined by the height of the obstacle directly under the foot but by the shape of the entire obstacle, including the opposite limb.

In the study of obstacle traversal, the findings suggest not only that the motor control of the lower limbs is independent, but also a new theory that the left and right legs are controlled by mutual motor influences. It is also proposed that motor control of the lower limb during the traversal of obstacles may be prioritized using a strategy of left-right foot control rather than foot elevation over the obstacle. In addition, quantitative as well as qualitative evaluation of the lower limb may allow for a more detailed evaluation of the motor control of this limb during the crossing of an obstacle.

Finally, this study elucidates the control of obstacle traversal in complex environments, similar to typical circumstances. It is expected that the findings of this study will facilitate a better understanding of the mechanism of falls associated with contact with obstacles, and more effectively address the social problem of accidental falls among the elderly, to minimize their occurrence.

Chapter 5.
General Discussion

Abstract (in Japanese)

本研究の目的は，障害物横断時の足の軌跡が障害物の形状によって異なる制御がされるかどうかを明らかにすることであった。本研究で得られた知見は、(1) 左右脚間の運動制御には相互作用が存在し、反対脚が跨いだ障害物の高さや、反対脚の運動が障害物跨ぎ越し歩行時の下肢の運動制御に影響を与える。(2) 不定形な障害物を跨ぐ際には、下肢の運動は鉛直方向だけではなく左右方向の制御も含めた、障害物全体の形状も考慮に入れて制御しているということである。(3) 健常者であっても非合理的な跨ぎ越し運動を行う可能性を示唆した。(4) 障害物越えの歩行における下肢の運動は、足の真下にある障害物の高さではなく、反対側の肢を含む障害物全体の形状によって決まるということである。

障害物跨ぎ越し歩行分野において、本研究から得られた知見は、「下肢の運動制御は独立している」という説だけではなく、「左右脚は相互に運動の影響を受けて制御がなされている」という新たな説を示唆するものである。また、障害物跨ぎ越し歩行における下肢の運動制御は、障害物の形状に応じて足部の挙上よりも、左右方向の足部の制御を行う戦略が優先される可能性を提唱する。加えて、定性的な下肢の評価だけではなく、定量的な評価を行うことで、より詳細に障害物跨ぎ越し歩行における、下肢の運動制御を評価できる可能性がある。

最後に、本研究は日常生活に近いより複雑な環境下での障害物跨ぎ越し歩行制御を明らかにした研究である。本研究で得られた知見は、障害物の接触による転倒機序の解明の一助となり、社会問題である高齢者の転倒問題の解決と、転倒予防方法の考案に繋がることが期待される。

1. Objectives and results of this study

The objective of this study was to determine whether the trajectory of the foot is influenced by the shape of an obstacle during its traversal. In Chapter 3, experiments were performed to compare the foot trajectories for the crossing of obstacles of different heights on the left and right sides, and the crossing of an obstacle of the same height on the left and right sides. It was determined that the foot trajectory when crossing an obstacle was affected not only by the height of the obstacle but also by the motion of the opposite leg and the height of the obstacle that the opposite leg crossed. In Chapter 4, for the tasks of crossing a trapezoidal obstacle and a rectangular obstacle, we established that the foot controls the lower limb not only in the vertical direction but also in the lateral direction, considering the shape of the entire obstacle. It was also determined that even healthy people may perform irrational locomotion. Based on the two experiments, it is evident that the motion of the lower limb during the crossing of an obstacle is not determined by the height of the obstacle directly under the foot, but by the shape of the entire obstacle, including the opposite limbs. In this chapter, we discuss the significance of the findings in Chapters 3 and 4 considering gait control and its anticipated contribution to human health.

2. Explanation of similarities and differences between Chapters 3 and 4

Chapter 3 presented the results for a task involving obstacles of different heights for traversal by the leading and trailing limbs. In Chapter 4, unlike Chapter 3, the obstacles to be traversed by the leading and trailing limbs were not set separately. Instead, a single trapezoid-shaped obstacle was crossed by the leading and trailing limbs. In the case of Chapter 4, the obstacles were crossed using not only vertical, but also lateral foot control, although the opposite leg was affected by the obstacle crossed and the motion of the opposite leg, and the foot was elevated. However, from a quantitative perspective, the participants performed lateral movements although the movement of the foot by 1 cm in the lateral direction only resulted in a height of 0.5 mm in the vertical direction, suggesting that the participants potentially performed irrational movements. The differences between the two studies are as follows: (1) The shape of the obstacle that was crossed was different, i.e., whether it was an obstacle divided into left and right sections or a trapezoidal obstacle combined to yield left and right sections; (2) When the shape of the obstacle was different, it was observed that the foot controlled not only vertical but also lateral movement. (3) It was observed that even healthy adults performed irrational movements. The findings from the two experiments indicate that the motion of the lower limb during the crossing of an obstacle is not determined by the height of the obstacle directly under the foot, but by the shape of the entire obstacle, including the opposite limbs.

3. Contribution to the field of gait control

The main findings are as follows: (1) There was an interaction in the motor control between the leading and trailing limbs, and the height of the obstacle crossed by the opposite leg and the motion of the opposite leg affected the motor control of the lower limb during the traversal of the obstacle. (2) When crossing an irregularly shaped obstacle, the motion of the lower limb was controlled not only in the vertical direction but also in the lateral direction, considering the shape of the obstacle. (3) This implies that even a healthy person may perform the irrational crossing-over motion. (4) The motion of the lower limb during the crossing of obstacles is not determined by the height of the obstacle directly under the foot, but by the shape of the entire obstacle, including the opposite limb. The implications of each finding in the field of gait control are discussed below.

First, (1) "There was an interaction in the motor control between the leading and trailing limbs. Moreover, the height of the obstacle crossed by the opposite leg and the motion of the opposite leg affects the motor control of the lower limb during the crossing of an obstacle". Previous adaptive gait studies have shown that lower limb movements were independently controlled [14,15]. The main concept is that the motion and feedback of one lower limb are not used to control the other. To adapt gait in various environments, it is necessary to use a variety of sensory information, including visual information. The three systems used to control walking locomotion are the visual, vestibular, and somatosensory systems [87]. Among these, visual information is needed to understand the surrounding environment. For example, if there is an obstacle in the walking path, the height, shape, and location of the obstacle must be visually assessed to make appropriate choices such as whether to step over, go around, or through the obstacle. In addition, the height, shape, and location of an obstacle obtained based on visual information are stored as a form of short-term memory called working memory [13], which is used to control the lower limbs. Humans can see obstacles when the leading leg moves over them, but not when the trailing leg traverses them. Heijnen et al. [12,31] discovered that this absence of visual feedback led to frequent obstacle contact with the trailing leg. They reported on the possibility of using context, perception, and working memory to compensate for this lack of information. In addition, they determined that when an obstacle is not visible, the lower limb must be guided over the obstacle using stored visuospatial representations [13,31,88,89]. Considering these findings, previous obstacle-crossing gait studies involved tasks in which the leading and trailing limbs crossed obstacles of the same height separately. In these investigations, the leading limb was the first limb to cross the obstacle and the following leg was the trailing limb [10]. Clearance was used as a typical index for evaluating lower limb motion in obstacle-crossing gait [10]. Clearance is the vertical distance between the foot and the obstacle. From previous studies, the factors that alter clearance include time constraints [25], aging [16], cognitive function [19], gender differences [18], obstacle height, and the depth of objects [9]. However, none of these studies focused on interactions in the motor control of the leading and trailing limbs. Moreover, the role of factors in the motor control of the lower limb such as the motion of the opposite leg and the height of the obstacle traversed by the opposite leg has not been elucidated. The findings of this study suggest not only a theory of independent motor control of the lower limb during the crossing of obstacles but also a new theory that the lower limb is influenced by the reciprocal motion of the leading and trailing limbs.

The finding that (2) when crossing an irregularly shaped obstacle, the lower limb motion was controlled not only in the vertical direction but also in the lateral direction is discussed considering the shape of the entire obstacle. In previous studies on the crossing of obstacles, vertical clearance was evaluated as the risk of contact with the obstacle [10]. To reduce this risk during overpass walking, one solution is to elevate the foot. In obstacle-crossing gait, lower limb movements are controlled based on an energy minimization strategy [12], and clearance is determined based on a trade-off between minimizing energy consumption and the risk of contact with the obstacle. However, Yamagata et al. (2021) [78] reported that the strategy of ensuring clearance by elevating the foot is not always a safe method of crossing obstacles because excessive foot elevation may lead to left-right instability. Thus, ensuring vertical clearance is not necessarily a safe way to cross an obstacle. In addition, the vertical MP1 position of the foot may have a greater energy cost compared to the case of lateral displacement. Slawinski et al. (2014) [77] reported that energy expenditure increases with foot elevation in healthy subjects. In addition, clearance during obstacle traversal decreases with the number of trials, indicating that the motor control strategy of the lower limb is based on an energy minimization strategy [12]. Thus, in this dissertation, it is proposed that the lower limb motor control based on the crossing of obstacles may be prioritized using a strategy that controls the foot in the mediolateral direction. This is associated with a low energy cost and can safely allow for the traversal of obstacles, rather than foot elevation, which has a high energy cost and induces instability, depending on the obstacle's geometry.

Thirdly, (3) the possibility that even healthy individuals may engage in irrational crossing-over movements was suggested. Human economic activity may be suboptimal because of limited information processing and limited computational power [90,91]. Irrespective of the type of exercise that is planned, the executed and planned exercises do not necessarily coincide owing to variability in the exercise [92]. Therefore, it is necessary to consider one's motion variability to set an optimal motion plan. However, Ota et al. (2019) [82] reported that motor planning in an upper limb reaching task was not optimal, even when participants were explicitly provided with visual feedback information on the variation of their movements from the target (motor uncertainty). Ota et al. (2019) [82] suggested that this non-optimization of exercise planning may be owing to limitations in our ability to use this information to perform calculations while accounting for reward-risk tradeoffs, even if we have the information needed to optimize the exercise plan. From a quantitative perspective in terms of energy consumption, it was not possible to determine whether crossing an obstacle with the foot elevated 0.5 mm or crossing an obstacle with the foot moved 1cm to the left or right would result in lower energy consumption. Moreover, no studies have been reported that identify the case in which the energy consumption is smaller. However, based on the reports of Ota et al. [82] and Simon [90,91], it is possible that the participants in the study had restricted cognitive ability, and were unable to optimize their exercise plans, resulting in irrational obstacle-crossing movements. Previous obstacle-crossing gait studies have compared healthy young adults and elderly subjects [16] and those at high and low risk of falling [27]. These studies evaluated obstacle contact risk in terms of the vertical clearance required to cross an obstacle, and only considered qualitative measures, such as the effects of aging and fall risk on clearance. This study examined the motor control of the lower limb during obstacle crossing in detail from a quantitative perspective. By conducting a quantitative evaluation of movement during the crossing of the obstacles, the possibility of irrational movement that cannot be detected based only on this approach was suggested.

Finally, (4) The motion of the lower limb during the crossing of obstacles is not determined by the height of the obstacle directly under the foot, but by the shape of the entire obstacle, including the opposite limb. In previous studies of obstacle-stepping gait, it has been suggested that memory functions contribute to the control of the trailing leg [19] and that the neural resources of memory based on visual input between the leading and trailing legs are shared [32]. Therefore, it has also been suggested that upper limb locomotion is under comprehensive motor control that includes the movement of the opposite limb and the movements that were performed before and after the movement [28–30]. These findings suggest that motor control of the lower limb in obstacle crossing may contribute to motor memory and feed-forward control. Previous studies have not focused on the interaction of movements between the left and right legs, and the influence of one leg on the other has not been clarified. When crossing over obstacles of different heights, both the leading and trailing legs need to control the lower limbs using motor memory and feed-forward control. The obstacles used in the past in obstacle crossing studies, which included hurdles and boxes, were rectangular with uniform heights on both sides. Thus, the effect of the height of the obstacle on the opposite leg's lower limb movement was not considered [10]. This investigation is the first known report on overpass gait using obstacles with different heights on the left and right sides. The results suggest that the motion of the lower limb during overpass is not determined by the height of the obstacle directly under the foot, but also by the motion of the opposite leg, the height of the obstacle to be crossed by the opposite leg, and the shape of the obstacle.

4. *Solving the fall problem*

Accidental falls in the elderly are more likely to result in sequelae such as fractures and bedridden patients compared to younger individuals, which can negatively impact health, independence, and quality of life [57]. It has been shown that the risk of falls is higher in women than in men, regardless of age [93,94]. Therefore, this problem represents an urgent social issue that must be addressed, and not only for the elderly. To minimize the occurrence of falls and improve the quality of life of patients, it is necessary to elucidate the underlying mechanisms.

The results of this study showed that motor control between the leading and trailing limbs during the crossing of an irregularly shaped obstacle is affected by the height and motion of the obstacle in the case of the opposite leg. Previous obstacle-crossing studies used obstacles of the same height for the left and right sides [10]. However, typical obstacles do not always have symmetrical and regular shapes. Therefore, it is necessary to conduct studies involving the traversal of obstacles in an environment that is more similar to the real world. In this study, a new experimental paradigm, the crossing of irregularly shaped obstacles, was investigated. This approach has not been used in previous studies on obstacle crossing. To safely step over an irregularly shaped obstacle, it is necessary to assess its shape and height based on visual information and to control the foot trajectory based on this data. When crossing obstacles of the same height on both sides, it is sufficient to raise the feet to the same height on both sides, which is a relatively simpler control when crossing regularly shaped obstacles. However, during the traversal of an irregularly shaped obstacle, the vertical and lateral distances between the foot and the obstacle differ depending on the position of the foot. Therefore, comprehensive control that includes not only the height of the obstacle directly under the foot but also the shape of the entire obstacle is necessary to avoid contact with it. The findings presented in this study allow for a deeper understanding of control during obstacle traversal in complex environments that are similar to that typical scenarios and is an important step in the elucidation of the mechanism of falls owing to contact with obstacles, as well as the prevention of falls in the elderly.

5. Limitations

The limitations of this study are that (1) the subjects were healthy young adults. Previous studies on obstacle traversal involved patients with Parkinson's disease [51,95], the elderly [16,19,26,27,96], and patients who suffered a stroke [85,97–99]. To devise a method to prevent falls owing to contact with obstacles while traversing them, it is necessary to conduct research not only on healthy young adults but also on subjects with different diseases and different age groups and to investigate the characteristics of each subject's lower limb movements by comparing the movements of each group. (2) In this investigation, only clearance was calculated, which means that the consideration of the results that the motion of the opposite leg and the height of the obstacle crossed by the opposite leg affected the clearance of the ipsilateral leg may be due to motor memory or feed-forward control is left to speculation. The clearance of both the leading and trailing legs was affected by the height of the obstacle that the opposite leg straddled and the motion of the opposite leg. Although the results suggest the existence of an interaction between the two legs, the factor that caused the greater clearance of the leading leg could not be explained by the interaction, suggesting the possibility of predictive motor control. Findings, such as the report that memory function has been shown to contribute to the control of the trailing leg in obstacle-stepping gait [19], the suggestion of shared neural resources of memory based on visual input between the leading and trailing limbs [32], and that upper limb movements, may be related to that of the opposite limb It has been suggested that upper limb movements may be under comprehensive motor control that includes the movements of the opposite limb and the type of movements that were performed before and after the movement [28–30]. These findings suggest that motor control of the lower limb during obstacle crossing may contribute to motor memory and feed-forward control. To confirm the existence of motor control interactions between the left and right legs, it is necessary to elucidate the relationship between memory function and feed-forward control mechanisms in obstacle-crossing gait.

Reference

[1] B. Senut, M. Pickford, D. Gommery, P. Mein, K. Cheboi, Y. Coppens, First hominid from the Miocene (Lukeino Formation, Kenya)., Comptes Rendus l'Academie Des Sci. Ser. 2A Sci. La Terre Des Planetes. 332 (2001) 137–144.

[2] M.D. Sockol, D.A. Raichlen, H. Pontzer, Chimpanzee locomotor energetics and the origin of human bipedalism, Proc. Natl. Acad. Sci. U. S. A. 104 (2007) 12265–12269. https://doi.org/10.1073/PNAS.0703267104.

[3] C. Owen Lovejoy, G. Suwa, L. Spurlock, B. Asfaw, T.D. White, The pelvis and femur of ardipithecus ramidus: The emergence of upright walking, Science (80-.). 326 (2009). https://doi.org/10.1126/SCIENCE.1175831.

[4] A.E. Patla, S.D. Prentice, C. Robinson, J. Neufeld, Visual Control of Locomotion: Strategies for Changing Direction and for Going Over Obstacles, J. Exp. Psychol. Hum. Percept. Perform. 17 (1991) 603–634. https://doi.org/10.1037/0096-1523.17.3.603.

[5] R. Moraes, M.A. Lewis, A.E. Patla, Strategies and determinants for selection of alternate foot placement during human locomotion: influence of spatial and temporal constraints, Exp. Brain Res. 159 (2004) 1–13. https://doi.org/10.1007/S00221-004-1888-Z.

[6] Aftad E. Patla, How Is Human Gait Controlled by Vision?, (1998) 287–302.

[7] D.B. Elliot, A. Vale, D. Whitaker, J.G. Buckley, Does my step look big in this? A visual illusion leads to safer stepping behaviour, PLoS One. 4 (2009) 2–7. https://doi.org/10.1371/journal.pone.0004577.

[8] Richard J. Foster, John G. Buckley, David Whitaker, David B. Elliott, The addition of stripes (a version of the 'horizontal-vertical illusion') increases foot clearance when crossing low-height obstacles, Ergonomics. 59 (2015) 884–889. https://doi.org/10.1080/00140139.2015.1105304.

[9] A. Patla, S. Rietdyk, Visual control of limb trajectory over obstacles during locomotion: effect of obstacle height and width, Gait Posture. 1 (1993) 45–60. https://doi.org/10.1016/0966-6362(93)90042-Y.

[10] B. Galna, A. Peters, A.T. Murphy, M.E. Morris, Obstacle crossing deficits in older adults: A systematic review, Gait Posture. 30 (2009) 270–275. https://doi.org/10.1016/j.gaitpost.2009.05.022.

[11] G.C. Avery, R.H. Day, Basis of the horizontal-vertical illusion, J. Exp. Psychol. 81 (1969) 376–380.

[12] M.J.H. Heijnen, B.C. Muir, S. Rietdyk, Factors leading to obstacle contact during adaptive locomotion, Exp. Brain Res. 223 (2012) 219–231.

https://doi.org/10.1007/s00221-012-3253-y.

[13] M. Shinya, A. Popescu, C. Marchak, B. Maraj, K. Pearson, Enhancing memory of stair height by the motor experience of stepping, Exp. Brain Res. 223 (2012) 405–414. https://doi.org/10.1007/s00221-012-3269-3.

[14] S. Anstis, Aftereffects from jogging, Exp Brain Res. 103 (1995).

[15] S. Rietdyk, C.K. Rhea, The effect of the visual characteristics of obstacles on risk of tripping and gait parameters during locomotion, Ophthalmic Physiol. Opt. 31 (2011) 302–310. https://doi.org/10.1111/J.1475-1313.2011.00837.X.

[16] B.C. Muir, J.M. Haddad, R.E.A. van Emmerik, S. Rietdyk, Changes in the control of obstacle crossing in middle age become evident as gait task difficulty increases, Gait Posture. 70 (2019) 254–259. https://doi.org/10.1016/j.gaitpost.2019.01.035.

[17] R. Sakurai, M. Montero-Odasso, H. Suzuki, S. Ogawa, Y. Fujiwara, Motor imagery deficits in high-functioning older adults and its impact on fear of falling and falls, Journals Gerontol. - Ser. A Biol. Sci. Med. Sci. 76 (2021) E228–E234. https://doi.org/10.1093/gerona/glab073.

[18] T.E. Raffegeau, G.K. Kellaher, M.J. Terza, J.A. Roper, L.J. Altmann, C.J. Hass, Older women take shorter steps during backwards walking and obstacle crossing,

Exp. Gerontol. 122 (2019) 60–66. https://doi.org/10.1016/j.exger.2019.04.011.

[19] R. Sakurai, K. Kodama, Y. Ozawa, F. Pieruccini-Faria, K.E. Kobayashi-Cuya, S. Ogawa, Association of age-related cognitive and obstacle avoidance performances, Sci. Rep. 11 (2021) 1–9. https://doi.org/10.1038/s41598-021-91841-9.

[20] I. Maidan, S. Eyal, I. Kurz, N. Geffen, E. Gazit, L. Ravid, N. Giladi, A. Mirelman, J.M. Hausdorff, Age-associated changes in obstacle negotiation strategies: Does size and timing matter?, Gait Posture. 59 (2018) 242–247. https://doi.org/10.1016/J.GAITPOST.2017.10.023.

[21] N.M. Rinaldi, J. Lim, J. Hamill, R. Van Emmerik, R. Moraes, Walking combined with reach-to-grasp while crossing obstacles at different distances, Gait Posture. 65 (2018) 1–7. https://doi.org/10.1016/J.GAITPOST.2018.06.167.

[22] C. Szu-Hua, L. On-Yee, K. Taylor, C. Li-Shan, Concurrent phone texting alters crossing behavior and induces gait imbalance during obstacle crossing, Gait Posture. 62 (2018) 422–425. https://doi.org/10.1016/J.GAITPOST.2018.04.004.

[23] S. Kim, M.A. Nussbaum, S. Ulman, Impacts of using a head-worn display on gait performance during level walking and obstacle crossing, J. Electromyogr. Kinesiol. 39 (2018) 142–148. https://doi.org/10.1016/J.JELEKIN.2018.02.007.

[24] K.W. Wu, J. Da Li, H.P. Huang, Y.H. Liu, T.M. Wang, Y.T. Ho, T.W. Lu, Bilateral asymmetry in kinematic strategies for obstacle-crossing in adolescents with severe idiopathic thoracic scoliosis, Gait Posture. 71 (2019) 211–218. https://doi.org/10.1016/j.gaitpost.2019.05.007.

[25] H. Chen, J.A. Ashton-miller, N.B. Alexander, A.B. Schultz, Effects of age and available response time on ability to step over an obstacle, J. Gerontol. Med. Sci. 49 (1994) 227–233. https://doi.org/10.1093/GERONJ/49.5.M227.

[26] R. Sakurai, Y. Fujiwara, M. Ishihara, T. Higuchi, H. Uchida, K. Imanaka, Age-related self-overestimation of step-over ability in healthy older adults and its relationship to fall risk, BMC Geriatr. 13 (2013). https://doi.org/10.1186/1471-2318-13-44.

[27] H.F. Pan, H.C. Hsu, W.N. Chang, J.H. Renn, H.W. Wu, Strategies for obstacle crossing in older adults with high and low risk of falling, J. Phys. Ther. Sci. 28 (2016) 1614–1620. https://doi.org/10.1589/jpts.28.1614.

[28] D. Nozaki, I. Kurtzer, S.H. Scott, Limited transfer of learning between unimanual and bimanual skills within the same limb, Nat. Neurosci. 9 (2006) 1364–1366. https://doi.org/10.1038/nn1785.

[29] I.S. Howard, D.M. Wolpert, D.W. Franklin, The value of the follow-through

derives from motor learning depending on future actions, Curr. Biol. 25 (2015) 397–401. https://doi.org/10.1016/j.cub.2014.12.037.

[30] I.S. Howard, C. Ford, A. Cangelosi, D.W. Franklin, Active lead-in variability affects motor memory formation and slows motor learning, Sci. Rep. 7 (2017) 1–12. https://doi.org/10.1038/s41598-017-05697-z.

[31] M.J.H. Heijnen, N.L. Romine, D.M. Stumpf, S. Rietdyk, Memory-guided obstacle crossing: More failures were observed for the trail limb versus lead limb, Exp. Brain Res. 232 (2014) 2131–2142. https://doi.org/10.1007/s00221-014-3903-3.

[32] S. Hagio, M. Kouzaki, Visuomotor transformation for the lead leg affects trail leg trajectories during visually guided crossing over a virtual obstacle in humans, Front. Neurosci. 14 (2020) 357. https://doi.org/10.3389/fnins.2020.00357.

[33] Y. Sekiguchi, K. Honda, S.-I. Izumi, Effect of walking adaptability on an uneven surface by a stepping pattern on walking activity after stroke, Front. Hum. Neurosci. 15 (2022) 746. https://doi.org/10.3389/FNHUM.2021.762223.

[34] A.R. Oates, A.E. Patla, J.S. Frank, M.A. Greig, Control of dynamic stability during gait termination on a slippery surface, J. Neurophysiol. 93 (2005) 64–70. https://doi.org/10.1152/JN.00423.2004/ASSET/IMAGES/LARGE/Z9K01204427

80008.JPEG.

[35] D.J. Liss, H.D. Carey, S. Yakovenko, J.L. Allen, Young adults perceive small disturbances to their walking balance even when distracted, Gait Posture. 91 (2022) 198–204. https://doi.org/10.1016/J.GAITPOST.2021.10.019.

[36] C.S. Baker, M.E. Cinelli, The effects of obstacle proximity on aperture crossing behaviours, Exp. Brain Res. 235 (2017) 497–506. https://doi.org/10.1007/s00221-016-4803-5.

[37] M.J.D. Caetano, S.R. Lord, D. Schoene, P.H.S. Pelicioni, D.L. Sturnieks, J.C. Menant, Age-related changes in gait adaptability in response to unpredictable obstacles and stepping targets, Gait Posture. 46 (2016) 35–41. https://doi.org/10.1016/j.gaitpost.2016.02.003.

[38] M.J.D. Caetano, J.C. Menant, D. Schoene, P.H.S. Pelicioni, D.L. Sturnieks, S.R. Lord, Sensorimotor and cognitive predictors of impaired gait adaptability in older people, J. Gerontol. A. Biol. Sci. Med. Sci. 72 (2017) 1257–1263. https://doi.org/10.1093/gerona/glw171.

[39] M.J.D. Caetano, S.R. Lord, M.A. Brodie, D. Schoene, P.H.S. Pelicioni, D.L. Sturnieks, J.C. Menant, Executive functioning, concern about falling and quadriceps strength mediate the relationship between impaired gait adaptability

and fall risk in older people, Gait Posture. 59 (2018) 188–192. https://doi.org/10.1016/j.gaitpost.2017.10.017.

[40] M.J.D. Caetano, S.R. Lord, N.E. Allen, J. Song, S.S. Paul, C.G. Canning, J.C.C. Menant, Executive functioning, muscle power and reactive balance are major contributors to gait adaptability in people with parkinson’s disease, Front. Aging Neurosci. 11 (2019) 154. https://doi.org/10.3389/fnagi.2019.00154.

[41] L.A. Vallis, B.J. McFadyen, Children use different anticipatory control strategies than adults to circumvent an obstacle in the travel path, Exp. Brain Res. 167 (2005) 119–127. https://doi.org/10.1007/S00221-005-0054-6/TABLES/6.

[42] A.L. Hackney, M.E. Cinelli, Young and older adults use body-scaled information during a non-confined aperture crossing task, Exp. Brain Res. 225 (2013) 419–429. https://doi.org/10.1007/S00221-012-3382-3/FIGURES/5.

[43] H.-C. Chen, J.A. Ashton-Miller, N.B. Alexander, A.B. Schultz, Stepping over obstacles: Gait patterns of healthy young and old adults, Oxford Academic, 1991. https://doi.org/10.1093/GERONJ/46.6.M196.

[44] A.E. Patla, E. Niechwiej, V. Racco, M.A. Goodale, Understanding the contribution of binocular vision to the control of adaptive locomotion, Exp. Brain Res. 142 (2002) 551–561. https://doi.org/10.1007/s00221-001-0948-x.

[45] J.S. Matthis, J.L. Yates, M.M. Hayhoe, C.B. Author, Gaze and the control of foot placement when walking in natural terrain HHS public access author manuscript, Curr. Biol. 28 (2018) 1224–1233. https://doi.org/10.1016/j.cub.2018.03.008.

[46] D.A. McVea, K.G. Pearson, Long-lasting memories of obstacles guide leg movements in the walking cat, J. Neurosci. 26 (2006) 1175–1178. https://doi.org/10.1523/JNEUROSCI.4458-05.2006.

[47] D.A. McVea, A.J. Taylor, K.G. Pearson, Long-lasting working memories of obstacles established by foreleg stepping in walking cats require area 5 of the posterior parietal cortex, J. Neurosci. 29 (2009) 9396–9404. https://doi.org/10.1523/JNEUROSCI.0746-09.2009.

[48] A. Kim, N. Schweighofer, J.M. Finley, Locomotor skill acquisition in virtual reality shows sustained transfer to the real world, J. Neuroeng. Rehabil. 16 (2019) 113. https://doi.org/10.1186/s12984-019-0584-y.

[49] K. Binaee, G.J. Diaz, Assessment of an augmented reality apparatus for the study of visually guided walking and obstacle crossing, Behav. Res. Methods. 51 (2019) 523–531. https://doi.org/10.3758/s13428-018-1105-9.

[50] J. Krell, A.E. Patla, The influence of multiple obstacles in the travel path on avoidance strategy, Gait Posture. 16 (2002) 15–19.

https://doi.org/10.1016/S0966-6362(01)00194-1.

[51] D. Orcioli-Silva, F.A. Barbieri, P.C.R. dos Santos, V.S. Beretta, L. Simieli, R. Vitorio, E. Lirani-Silva, L.T.B. Gobbi, Double obstacles increase gait asymmetry during obstacle crossing in people with Parkinson’s disease and healthy older adults: A pilot study, Sci. Rep. 10 (2020) 1–8. https://doi.org/10.1038/s41598-020-59266-y.

[52] Z. Wang, J.H. Chien, K.C. Siu, Stepping over multiple obstacles changes the pattern of foot integrated pressure of the leading and trailing legs, J. Biomech. 98 (2020) 109423. https://doi.org/10.1016/J.JBIOMECH.2019.109423.

[53] J.R. Berard, L.A. Vallis, Characteristics of single and double obstacle avoidance strategies: A comparison between adults and children, Exp. Brain Res. 175 (2006) 21–31. https://doi.org/10.1007/S00221-006-0529-0/FIGURES/5.

[54] M. Soma, H. Nakae, T. Abiko, R. Shimamura, H. Uematsu, K. Kawama, Influence of a dual task while stepping over an obstacle in the fall-experienced elderly people, J.Phys. Ther. Sci. 23 (2011) 369–372.

[55] D. Commandeur, M.D. Klimstra, S. MacDonald, K. Inouye, M. Cox, D. Chan, S.R. Hundza, Difference scores between single-task and dual-task gait measures are better than clinical measures for detection of fall-risk in community-dwelling

older adults, Gait Posture. 66 (2018) 155–159. https://doi.org/10.1016/j.gaitpost.2018.08.020.

[56] D.A. Jehu, D. Saunders, N. Richer, N. Paquet, Y. Lajoie, The influence of carrying an anterior load on attention demand and obstacle clearance before, during, and after obstacle crossing, Exp. Brain Res. 237 (2019) 3313–3319. https://doi.org/10.1007/s00221-019-05673-1.

[57] A.J. Blake, K. Morgan, M.J. Bendall, H. Dallosso, S.B.J. Ebrahim, T.H.D. Arie, P.H. Fentem, E.J. Bassey, Falls by elderly people at home: prevalence and associated factors, Age Ageing. 17 (1988) 365–372. https://doi.org/10.1093/ageing/17.6.365.

[58] H.J. Lipscomb, J.E. Glazner, J. Bondy, K. Guarini, D. Lezotte, Injuries from slips and trips in construction, Appl. Ergon. 37 (2006) 267–274. https://doi.org/10.1016/j.apergo.2005.07.008.

[59] P. Kannus, H. Sievänen, M. Palvanen, T. Järvinen, J. Parkkari, Prevention of falls and consequent injuries in elderly people, Lancet. 366 (2005) 1885–1893. https://doi.org/10.1016/S0140-6736(05)67604-0.

[60] M.E. Hahn, H.J. Lee, L.S. Chou, Increased muscular challenge in older adults during obstructed gait, Gait Posture. 22 (2005) 356–361.

https://doi.org/10.1016/j.gaitpost.2004.11.012.

[61] W.P. Berg, H.M. Alessio, E.M. Mills, C. Tong, Circumstances and consequences of falls in independent community-dwelling older adults, Age Ageing. 26 (1997) 261–268. https://doi.org/10.1093/ageing/26.4.261.

[62] J.H. Chien, J. Post, K.C. Siu, Effects of aging on the obstacle negotiation strategy while stepping over multiple obstacles, Sci. Rep. 8 (2018) 8576. https://doi.org/10.1038/s41598-018-26807-5.

[63] G.P. Austin, G.E. Garrett, R.W. Bohannon, Kinematic analysis of obstacle clearance during locomotion, Gait Posture. 10 (1999) 109–120. https://doi.org/10.1016/S0966-6362(99)00022-3.

[64] H.L. Chen, T.W. Lu, Comparisons of the joint moments between leading and trailing limb in young adults when stepping over obstacles, Gait Posture. 23 (2006) 69–77. https://doi.org/10.1016/j.gaitpost.2004.12.001.

[65] N. van Melick, B.M. Meddeler, T.J. Hoogeboom, M.W.G. Nijhuis-van der Sanden, R.E.H. van Cingel, How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults, PLoS One. 12 (2017) e0189876. https://doi.org/10.1371/journal.pone.0189876.

[66] S. Cornus, G. Montagne, M. Laurent, Perception of a Stepping-Across

Affordance, Ecol. Psychol. 11 (1999) 249–267. https://doi.org/10.1207/s15326969eco1104_1.

[67] W.H. Warren, Perceiving affordances: Visual guidance of stair climbing., J. Exp. Psychol. Hum. Percept. Perform. 10 (1984) 683–703. https://doi.org/10.1037/0096-1523.10.5.683.

[68] K.G. Pearson, N. Arbabzada, R. Gramlich, M. Shinya, Leg mechanics contribute to establishing swing phase trajectories during memory-guided stepping movements in walking cats: a computational analysis, Front. Comput. Neurosci. 9 (2015) 8. https://doi.org/10.3389/fncom.2015.00116.

[69] R. Sakurai, Y. Fujiwara, M. Yasunaga, H. Suzuki, Y. Murayama, K. Imanaka, K. Kanosue, K. Ishii, Neural correlates of older adults' self-overestimation of stepping-over ability, Age (Omaha). 38 (2016) 351–361. https://doi.org/10.1007/s11357-016-9932-z.

[70] R.P. Di Fabio, W.M. Kurszewski, E.E. Jorgenson, R.C. Kunz, Footlift asymmetry during obstacle avoidance in high-risk elderly, J. Am. Geriatr. Soc. 52 (2004) 2088–2093. https://doi.org/10.1111/j.1532-5415.2004.52569.x.

[71] K. Pearson, R. Gramlich, Updating neural representations of objects during walking, Ann. N. Y. Acad. Sci. 1198 (2010) 1–9. https://doi.org/10.1111/j.1749-

6632.2009.05422.x.

[72] P. Kannus, H. Sievänen, M. Palvanen, T. Järvinen, J. Parkkari, Prevention of falls and consequent injuries in elderly people, Lancet. 366 (2005) 1885–1893. https://doi.org/10.1016/S0140-6736(05)67604-0.

[73] H.J. Lipscomb, J.E. Glazner, J. Bondy, K. Guarini, D. Lezotte, Injuries from slips and trips in construction, Appl. Ergon. 37 (2006) 267–274. https://doi.org/10.1016/j.apergo.2005.07.008.

[74] D. Muroi, S. Ohtera, Y. Kataoka, M. Banno, Y. Tsujimoto, H. Tsujimoto, T. Higuchi, Obstacle avoidance training for individuals with stroke: A systematic review and meta-analysis, BMJ Open. 9 (2019). https://doi.org/10.1136/bmjopen-2018-028873.

[75] A.A. Mohagheghi, R. Moraes, A.E. Patla, The effects of distant and on-line visual information on the control of approach phase and step over an obstacle during locomotion, Exp. Brain Res. 155 (2004) 459–468. https://doi.org/10.1007/s00221-003-1751-7.

[76] C.M. Said, M. Galea, N. Lythgo, Obstacle crossing following stroke improves over one month when the unaffected limb leads, but not when the affected limb leads, Gait Posture. 39 (2014) 213–217.

https://doi.org/10.1016/j.gaitpost.2013.07.008.

[77] J. Slawinski, D. Pradon, D. Bensmail, N. Roche, R. Zory, Energy cost of obstacle crossing in stroke patients, Am. J. Phys. Med. Rehabil. 93 (2014) 1044–1050. https://doi.org/10.1097/PHM.0000000000000122.

[78] M. Yamagata, H. Tateuchi, T. Pataky, I. Shimizu, N. Ichihashi, Relation between frontal plane center of mass position stability and foot elevation during obstacle crossing, J. Biomech. 116 (2021) 110219. https://doi.org/10.1016/J.JBIOMECH.2020.110219.

[79] Y. Miura, M. Shinya, Foot clearance when crossing obstacles of different heights with the lead and trail limbs, Gait Posture. 88 (2021) 155–160. https://doi.org/10.1016/J.GAITPOST.2021.05.020.

[80] S.W. Wu, M.R. Delgado, L.T. Maloney, Economic decision-making compared with an equivalent motor task, Proc. Natl. Acad. Sci. U. S. A. 106 (2009) 6088–6093. https://doi.org/10.1073/PNAS.0900102106/SUPPL_FILE/0900102106SI.PDF.

[81] D.M. Wolpert, M.S. Landy, Motor control is decision-making, Curr. Opin. Neurobiol. 22 (2012) 996–1003. https://doi.org/10.1016/J.CONB.2012.05.003.

[82] K. Ota, M. Shinya, L.T. Maloney, K. Kudo, Sub-optimality in motor planning is

not improved by explicit observation of motor uncertainty, Sci. Rep. 9 (2019) 1–11. https://doi.org/10.1038/s41598-019-50901-x.

[83] K. Ota, M. Shinya, K. Kudo, Motor planning under temporal uncertainty is suboptimal when the gain function is asymmetric, Front. Comput. Neurosci. 9 (2015) 88. https://doi.org/10.3389/FNCOM.2015.00088.

[84] K. Ota, M. Shinya, K. Kudo, Sub-optimality in motor planning is retained throughout 9 days practice of 2250 trials, Sci. Rep. 6 (2016) 1–12. https://doi.org/10.1038/srep37181.

[85] C.M. Said, Mary Galea, Noel Lythgo, Obstacle crossing performance does not differ between the first and subsequent attempts in people with stroke, Gait Posture. 30 (2009) 455–458. https://doi.org/10.1016/J.GAITPOST.2009.07.004.

[86] C.M. Said, P.A. Goldie, A.E. Patla, W.A. Sparrow, Effect of stroke on step characteristics of obstacle crossing, Arch. Phys. Med. Rehabil. 82 (2001) 1712–1719. https://doi.org/10.1053/APMR.2001.26247.

[87] Eric R.Kandel, James H. Schwartz, Jessell T.M., Siegelbaum S., Hudspeth A. J., Mack S, Keir G.Pearson, James E.Gordon, Principles of Neural Science, in: Fifth edit, McGraw-Hill, New York, 2000: pp. 821–833.

[88] A.A. Mohagheghi, R. Moraes, A.E. Patla, The effects of distant and on-line

visual information on the control of approach phase and step over an obstacle during locomotion, Exp. Brain Res. 155 (2004) 459–468. https://doi.org/10.1007/S00221-003-1751-7/TABLES/1.

[89] N.C.W. Chu, D.L. Sturnieks, S.R. Lord, J.C. Menant, Visuospatial working memory and obstacle crossing in young and older people, Exp. Brain Res. (2022). https://doi.org/10.1007/S00221-022-06458-9.

[90] H.A. Simon, A behavioral model of rational choice, Q. Jounal Econ. 63 (1955) 99–118. https://academic.oup.com/qje/article/69/1/99/1919737 (accessed November 12, 2022).

[91] H.A. Simon, Rational choice and the structure of the environment, Psychol. Rev. 63 (1956) 129–138.

[92] R.J. Van Beers, P. Haggard, D.M. Wolpert, The role of execution noise in movement variability, J. Neurophysiol. 91 (2004) 1050–1063. https://doi.org/10.1152/JN.00652.2003/ASSET/IMAGES/LARGE/Z9K0020436870012.JPEG.

[93] J.A. Stevens, E.D. Sogolow, Gender differences for non-fatal unintentional fall related injuries among older adults, Inj. Prev. 11 (2005) 115–119. https://doi.org/10.1136/IP.2004.005835.

[94] H.Y. Cho, M.J.H. Heijnen, B.A. Craig, S. Rietdyk, Falls in young adults: The effect of sex, physical activity, and prescription medications, PLoS One. 16 (2021) 1–19. https://doi.org/10.1371/journal.pone.0250360.

[95] R. Vitório, E. Lirani-Silva, A.M. Baptista, F.A. Barbieri, P.C.R. Dos Santos, C. Teixeira-Arroyo, L.T.B. Gobbi, Disease severity affects obstacle crossing in people with Parkinson's disease, Gait Posture. 40 (2014) 266–269. https://doi.org/10.1016/J.GAITPOST.2014.03.003.

[96] R. Sakurai, K. Kodama, Y. Ozawa, Adaptive locomotion during subtle environmental changes in younger and older adults, Sci. Rep. 12 (2022) 12438. https://doi.org/10.1038/S41598-022-16436-4.

[97] N. Chen, X. Xiao, H. Hu, Y. Chen, R. Song, L. Li, Identify the alteration of balance control and risk of falling in stroke survivors during obstacle crossing based on kinematic analysis, Front. Neurol. 10 (2019) 813. https://doi.org/10.3389/fneur.2019.00813.

[98] L.C. Benson, S.C. Cobb, A.S. Hyngstrom, K.G. Keenan, J. Luo, K.M. O'Connor, Identifying trippers and non-trippers based on knee kinematics during obstacle-free walking, Hum. Mov. Sci. 62 (2018) 58–66. https://doi.org/10.1016/J.HUMOV.2018.09.009.

[99] K. Takatori, Y. Okada, K. Shomoto, K. Ikuno, K. Nagino, K. Tokuhisa, Effect of a cognitive task during obstacle crossing in hemiparetic stroke patients, Physiother. Theory Pract. 28 (2012) 292–298. https://doi.org/10.3109/09593985.2011.600424.

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