Spring 5-8-2021

The effect of obstacle intervals on foot integrated pressure and obstacle negotiation strategy

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By

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A THESIS

Presented to the Faculty of

the University of Nebraska Graduate College

in Partial Fulfillment of the Requirements

for the Degree of Master of Science

Medical Sciences Interdepartmental Area Graduate Program

(Physical Therapy)

Under the Supervision of Professor Ka-Chun (Joseph) Siu

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April, 2021

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Acknowledgement

I would like to extend my sincere thanks to my committee members for their assistance at every stage of this research project. I would also like to thank Dr. Jung Hung Chien for his insightful suggestions and invaluable help with my data collection and analysis process. I would like to thank my family and friends for their love and support throughout my study. Moreover, I want to thank China Scholarship Council for providing me with the scholarship to support my study at UNMC. Finally, parts of the original article published on Journal of Biomechanics (Wang et al., 2020) are included in this thesis.

The effect of obstacle intervals on foot integrated pressure and obstacle negotiation strategy

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When stepping over a single obstacle, despite of some spatiotemporal parameter changes, the impulse of the leading and trailing leg stays the same. This is considered an efficient obstacle avoidance strategy. However, research has shown that the strategy of multiple obstacles negotiation is different from a single obstacle crossing. Would this efficient strategy still exist during multiple obstacles negotiation? This study attempted to answer this question. Nineteen healthy young adults were recruited in this study. Each participant was required to complete 15 trials under 3 conditions: one-step, two-step, and three-step intervals. Data were collected for foot integrated pressure (FIP), walking velocity and spatiotemporal gait parameters of horizontal distance (HD) and vertical distance (VD). A three-way repeated measures ANOVA was used for analyses. Significant interactions were found on walking speed ($p = 0.001$), FIP ($p < 0.0001$), HD ($p = 0.001$), and VD ($p < 0.0001$). When the interval was two-step and three-step, a significantly increased FIP was found in the leading leg than the trailing leg at the second obstacle ($p < 0.001$, $p < 0.001$). This higher FIP was consistent with higher VD ($p < 0.05$, $p < 0.05$) and longer HD ($p < 0.01$, $p < 0.01$) of the leading leg. This study showed that the presence of the second obstacle changed the strategy of obstacle negotiation no matter whether the interval was one, two, or three steps. As suggested by FIP, in healthy young adults, the obstacle negotiation strategy was inefficient when stepping over the second obstacle.

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List of Abbreviation

Fix4-6	Gaze fixation at the 4-6 m region on the walkway
COM	Center of mass
FIP	Foot integrated pressure
HD	Horizontal distance
VD	Vertical distance
S1	One-step interval
S2	Two-step interval
S3	Three-step interval
Ob1	First obstacle
Ob2	Second obstacle

Chapter 1. Introduction

The link between falls and obstacle negotiation

Falling is becoming a serious concern of public health and is considered the second leading cause of accidental injury deaths worldwide (WHO, 2020). Each year, there are 37.3 million falls requiring medical attention, causing a substantial burden on healthcare system (WHO, 2020). Many causes lead to falls, such as tripping, slipping, misplaced stepping, loss of balance, legs giving way, knocked over, and loss of support surfaces (Berg et al., 1997). Among all the causes, tripping over obstacles contributes to 47% of fall accidents, and it is considered one of the most prevalent reasons for falls (Berg et al., 1997; Campbell et al., 1990). Thus, it is necessary to understand the mechanism of obstacle avoidance to negotiate obstacles safely and avoid tripping to prevent falls.

When stepping over an obstacle, individuals would cross the obstacle using the leading leg first, followed by the trailing leg. It is suggested that there might be an optimal strategy to adjust the trajectories of the leading and the trailing leg to avoid tripping and step over the obstacle successfully (Novak and Deshpande, 2014). Notably, the trajectory of the leading leg is different from the trajectory of the trailing leg when crossing an obstacle (Park and Lee, 2012). In their study, nine healthy young adults and nine healthy elderly adults were instructed to step over obstacles of 10%, 20%, and 30% of the leg length. The results showed that, despite of obstacle height, the maximum hip flexion in the mid-swing phase for the leading leg was significantly higher compared to the trailing leg. And the maximum ankle dorsiflexion in the late swing phase for the leading leg was higher than the trailing leg. On the contrary, the maximum ankle plantarflexion in late stance phase for the leading leg was smaller than the trailing leg.

Obstacle negotiation strategies

The literature supports several mechanisms to explain the different trajectories between the leading and the trailing leg when individuals negotiate an obstacle, such as vision pre-programming and somatosensory information transfer. When the trailing leg passes through the obstacle, there is no visual input at this specific moment. Therefore, either vision needs to provide the environment information ahead to prepare the trajectories, or the leading leg will transfer the environment information from one leg to the other leg.

Several studies suggested the concept of vision pre-programming. (Weerdesteyn et al., 2004; Patla et al., 1991; Palta and Vickers, 1997; Palta and Vickers, 2003). Weerdesteyn and colleagues (2004) compared the latencies of obstacle avoidance reaction with latencies of voluntary stride modifications and simple reaction times of hand and foot. An obstacle was held with a magnet and would fall in front of participants' legs when they were walking on the treadmill. And the foot accelerations were measured to detect the latency of obstacle avoidance reaction. The latency of the obstacle avoidance reaction was defined as the moment when the foot acceleration curve deviated from the control signal. The task to measure latency of voluntary stride modification was to switch between the long stride strategy and short stride strategy on the cue by Plato Spectacles glasses. As for the simple reaction task of hand, participants were required to release the bottom as soon as possible when a light was illuminated. Similarly, the simple reaction task for the foot was to dorsiflex the foot when given a cue by Plato Spectacles. The average latencies of obstacle avoidance reactions were 122±14ms and were significantly shorter than latencies of voluntary stride modification and simple reaction times of hand and foot, which indicated the involvement of subcortical pathways in obstacle avoidance. Therefore, there should exist a proactive mechanism in human brains to pre-program the strategy for obstacle crossing rather than just reactive.

Patla and Vickers (1997) explored where and when to look at as people approach and step over an obstacle. They analyzed spatiotemporal gaze patterns by having eight participants wearing a mobile eye tracker to approach and step over obstacles. The obstacles were 1cm, 15cm, or 30cm in height and were placed at a random location 4-6m away on the walkway from the starting point. The types of gaze fixation were defined based on the locations in the walkway. They were classified as obstacle fixation, travel fixation (the gaze was stable and traveling at the speed of the whole body as individuals walked), and fixation in the 4-6m region (Fix4-6). The authors examined the frequency and duration of these three types of gaze fixation and found that participants fixated on steps before the obstacle for planning rather than on the obstacle they were stepping over. Moreover, Fix4-6 duration was higher in the step before and stepped over the obstacle, which indicated for the visual search for the landing area after the leading leg stepped over the obstacle. These results showed that the visual information for obstacle crossing is used in a feedforward manner instead of on-line control to regulate locomotion.

When Patla and Vickers (2003) further investigated how far ahead to look at when stepping on a specific location by requiring participants to step on 17 footprints, either regularly or irregularly placed in the travel path. They found two types of gaze fixation were used, which were footprint fixation and travel fixation. And travel gaze fixation was the dominant gaze behavior. They hypothesized that travel gaze fixation would allow participants to receive information from optic flow to guide the movement. Moreover, they found that individuals would fixate on the area two steps ahead to allow them sufficient time to adjust their gait.

In short, the premise of vision pre-programming suggests that the trajectories of the leading and the trailing leg are determined proactively by vison two steps away before stepping over the obstacle.

As for the concept of somatosensory information transfer, researchers attribute the different trajectories of the leading and the trailing leg to information transferred by the leading leg. Hedel and colleagues (2002) studied how new locomotor skill transferred in the mirror condition. They asked participants to step over an obstacle on the treadmill for two consecutive runs using the same leading leg. The vision was blocked by glasses, and the appearance of the obstacle was signaled by audio cues. For the third run, the leading leg and the trailing leg were switched. After analyzing leg muscle electromyographic, joint angle, and foot clearance, they found that all measures, except ankle trajectory, showed adaptational changes and transferred to the mirror condition. This study suggested that information could be transferred from the leading leg to the trailing leg primarily through the somatosensory system. Chien et al. (2018) further confirmed that the leading leg could transfer the information about the size and height of an obstacle to the trailing leg after the leading leg crossed the obstacle.

To summarize, the vision pre-programs and sets the trajectories two steps in advance. Simultaneously, the somatosensory system plays an important role in transferring the information of the size and height of an obstacle from the leading leg to the trailing leg.

The two systems work together to form a successful obstacle avoidance strategy and contribute to the different trajectories of the two legs.

Efficient strategy for single obstacle negotiation

Human walking is considered efficient energetically (Halsey and White, 2019). And the energy consumption is usually measured by metabolic energy expenditure using oxygen consumption or by mechanic work (Huang and Kuo, 2014). Awad and colleagues explored the relationship between energy cost and spatiotemporal gait symmetry in patients after stroke. The energy cost of walking was measured by oxygen consumption per meter walked and was normalized to body weight and walking speed (ml O2/kg/m). Spatiotemporal gait parameters, including walking speed, step length, swing time, and stance time, were collected using an 8-camera motion capture system. The results indicated that more symmetric walking correlated with more advantageous energy costs (Awad et al., 2015). Thus, in order to walk more efficiently, the energy consumption should be similar between the leading and the trailing leg, although the trajectories of these two are different.

Furthermore, Huang and Kuo (2014) used the inverse dynamic model to measure the mechanical work performed on the center of mass (COM) during walking. The mechanical work was measured by the power, which was the integral of the leg's ground reaction force against the COM velocity. The power of the COM was defined negative if generated by the leading leg and positive if generated by the trailing leg. Their results showed that, within a gait cycle, the negative power of COM was the same as the positive power of COM between the leading and trailing leg. This finding indicated the existence of energy efficiency in human walking reflected by mechanical work.

For stepping over an obstacle, does this efficiency still exist? As mentioned above, the toe clearances, the maximum hip flexion in the mid-swing phase, the maximum ankle dorsiflexion in the late swing phase, and the maximum ankle plantarflexion in the late stance phase are significantly different between the leading and the trailing legs (Park and Lee, 2012). Would these kinematic changes affect efficiency when stepping over an obstacle?

Researchers use the impulse to examine the kinetics of the leading leg and the trailing leg for obstacle avoidance. The impulse equals net force times the time interval. Bovonsunthonchai and colleagues (2015) recruited 13 healthy young women to step over obstacles under four conditions: no obstacle, 5cm-height obstacle, 20cm-height obstacle, and 30cm-height obstacle. Force data of the leading and the trailing leg were collected from two force plates. The results showed that the kinetic data of the total impulse of the leading leg and the trailing leg were similar no matter how high the obstacle, Thus, it may be inferred that the energy efficiency still presents in obstacle negotiation. And this efficient strategy adjusts the kinematic changes to make the leading leg and the trailing leg contribute equal impulse when stepping over an obstacle.

Similar to the power and impulse, the foot integrated pressure (FIP) is also a kinetic parameter used to investigate gait patterns (Giacomozzi et al., 2000). FIP is defined as the integral of pressure over the time interval. A study investigating the foot pressure distribution in young and older adults showed similar results between pressure and force data (Hessert et al., 2005). This indicated that investigating force data and measuring foot pressure data can both reflect gait changes in young and older adults. Specifically, FIP has been used to investigate the effect of age and gender on human gait patterns (McKay et al., 2017). They recruited 1000 healthy individuals aged from 3 to 101 years old to establish the normative reference for spatiotemporal and plantar pressure parameters. And from the physical mechanics perspective, the impulse is the integral of a force over the time interval, while the FIP is the integral of a force applied to the area over the time interval. If the surface areas are the same between the leading and the trailing leg, the impulse and the FIP can be recognized as the same parameter and can be used interchangeably. Thus, it is feasible to use FIP to identify the strategy of obstacle crossing.

Another reason to use FIP to explore the obstacle negotiation is that the pressure mat is more portable compared to a fixed force plate. Due to the fixed placement of the force plate, it requires different trials to obtain data from the leading and the trailing leg respectively, which might increase errors. On the contrary, a Zeno pressure walkway (0.8m x 6m active area, ProtoKinetics, Havertown, PA, USA) allows researchers to obtain FIP of both legs in the same trial. Moreover, the Zeno walkway has been validated by several studies to measure pressure and spatiotemporal gait parameters (Lynall et al., 2017; Padula et al.,2015; Berg-Poppe et al., 2018; McKay et al.,2017; Vallabhalosula et al., 2019). Therefore, it is valid and reliable to use the Zeno walkway to measure FIP in obstacle negotiation.

Given the preceding evidence and based on the findings of Huang and Kuo (2014) and Bovonsunthonchai et al. (2015), it is hypothesized that, for an efficient obstacle crossing, the FIP of the leading and the trailing leg should be equal.

The differences between single and multiple obstacles negotiation

However, previous literature only explored on single obstacle crossing. (Novak and Deshpande, 2014; Park and Lee, 2012; Weerdesteyn et al., 2004; Hedel et al., 2002; Bovonsunthonchai et al., 2015). Investigating the kinetic and kinematic gait parameters between the leading and the trailing legs when stepping over a single obstacle may not reflect the complexity of this movement in a real-world setting. For instance, the number of multigenerational households increased from 42.4 million in 2000 to 64 million in 2016 (United States Census, 2016). One-fifth of American households are multigenerational which may increase unpredictability or create obstacles in the environment. Older adults may need to be cautious to step over if there are young kids around. Moreover, a study has shown that training of stepping over multiple obstacles would significantly improve walking speed in post-stroke patients (Jaffe et al., 2004). However, the reason behind the training effect is unknown, and the basic knowledge of multiple obstacles crossing strategy is still limited.

Research studies show that the strategy of stepping over multiple obstacles is different from the strategy of stepping over a single obstacle (Chien et al., 2018; Krell and Patla, 2002; Berard and Vallis, 2006). Krell and Patla (2002) asked participants to complete 120 random trials under eight test conditions: no obstacle, a single obstacle at 0, 1m, 1.5m, and 2 m position, and double obstacles at 0 and 1, 0 and 1.5 and 0 and 2 m positions. And they used toe-off-to-obstacle distance and toe clearance to measure the obstacle avoidance strategies. They found that the presence of a second obstacle influenced the toe-off-to-obstacle distance in the trailing leg for the first and the second obstacle. More specifically, the toe-off-to-obstacle distance in the trailing leg was modified by the position of the second obstacle. When the distance between the two obstacles was 1m, the toe-off-to-obstacle distance of the trailing leg was shorter compared to other conditions when stepped over the first obstacle. As for the second obstacle, the toe-off-to-obstacle distance of the trailing leg was shorter when the interval was 1.5m compared to other interval distances. The results indicated that the presence of the second obstacle influences obstacle avoidance strategy, and the change of spatiotemporal parameters are highly correlated to the interval distance between the two obstacles.

In a study comparing single and double obstacle crossing (1.5m interval) in adults and children (Berard and Vallis, 2006), the toe clearance of the trailing leg showed a significant difference in double obstacles compared to single obstacle condition for both adults and children. For adults, the toe clearance of the trailing leg when stepping over the second obstacle was lower than the single obstacle clearance. And for the kids, the toe clearance of the trailing leg when stepping over the first obstacle was significantly lower when comparing with the single obstacle condition. This result indicated that both adults and children need to adjust their strategy for obstacle negotiation when there are multiple obstacles compared to a single obstacle.

Chien et al. (2018) further confirmed that the obstacle avoidance strategies would differ in multiple obstacle conditions, and the strategies are modified based on the distance between the two obstacles. Their results were consistent with previous studies (Krell and Patla, 2002; Berard and Vallis, 2006) by observing an increase in the toe clearance of the trailing leg in healthy young adults when the interval between obstacles was three steps away.

Knowledge gap

However, how do these changes of kinematic gait parameters affect the kinetic gait parameters when crossing multiple obstacles? How do the different intervals between obstacles influence the FIP and other kinematic data? The information is still unknown. Currently, there is no study examining FIP in the leading and the trailing leg when stepping over multiple obstacles. The purpose of my research is to investigate the change of the FIP to understand the strategies involved in multiple obstacle avoidance. Therefore, my research will explore the following research questions: 1) Would FIP and other kinematic parameters differ when stepping over the second obstacle compared to stepping over the first obstacle? 2) If yes, when would these differences occur – at the interval of one-step, two-step, or three-step? 3) Is there an efficient strategy in multiple obstacle crossing reflected by FIP? My central hypothesis is that the presence of the second obstacle would induce significant differences in FIP and kinematic parameters when stepping over the second obstacle regardless of the interval is one-step, two-step, or three-step. Moreover, the strategy in multiple obstacles crossing would be inefficient reflected by difference in FIP between the leading and trailing legs.

Chapter 2. Methods

Participants

Nineteen healthy young adults (8 males and 11 females, 25.84 ± 4.35 years old, Table 1) were included in this study. Participants were recruited by fliers and word of mouth. Participants were screened by the following inclusion and exclusion criteria.

Inclusion criteria included participants who were free from any neurological or musculoskeletal problems and who had no recent history of lower extremity injuries that might have affected their walking, such as having osteoarthritis, muscle strain, gout, neuropathy, vertigo and having dementia, stroke, Parkinson disease, vestibular disorders and any other diseases in circulation issues.

Exclusion criteria included individuals with neurological or musculoskeletal problems listed as listed above and individuals with a history of falling within the past year prior to data collection.

The study was approved by the University of Nebraska Medical Center Institutional Review Board (IRB# 338-17-FB).

Table 1. Characteristics of participants

SUBJECT	AGE	HEIGHT(CM)	WEIGHT(KG)	LEG LENGTH(CM)
1	25	176	66	100
2	28	167	50	83
3	38	156	49	79
4	26	171	70	90
5	27	175	66	90
6	24	171	65	87
7	24	165	63	85
8	22	176	73	90
9	23	166	55	83
10	24	165	62	85
11	25	176	64	90
12	22	182	64	90
13	22	182	76	94
14	24	167	53	82
15	36	174	81	89
16	26	177	73	89
17	23	180	74	92
18	28	179	72	90
19	24	180	65	90
AVERAGE ± SD	25.84 ± 4.35	172.89 ± 7.03	65.32 ± 8.82	88.32 ± 4.77

Experimental materials

Two PVC-crafted pipes (shape: cylinder, height: 0.6 m, radius: 0.02 m) were used as obstacles and were placed on the walkway at the height of 10% of participants' leg length. Qualisys motion capture system (Qualisys AB, Gothenburg, Sweden) and retro-reflective markers were used to obtain spatiotemporal gait parameters. A total of eight markers were placed on heels and first metatarsophalangeal joint of both legs as well as both ends of two obstacles. Qualisys motion capture system was used to capture the motion of these markers with Qualisys Tracker Manager software at 100 Hz.

Four events were captured: toe off of the trailing leg, heel strike of the leading leg, and toe clearance of the leading and trailing leg (Figure 1). Multiple spatiotemporal kinematic parameters were measured. The horizontal distance (HD) of the leading leg was measured as the horizontal distance between the heel of the leading leg and the obstacle when the heel of the leading leg contacts the ground. The HD of the trailing leg was calculated as the horizontal distance between the toe of the trailing leg and the obstacle when the trailing leg's toe pushed off the ground. The vertical distance (VD) of the leading leg was assessed as the vertical distance between the toe of the leading leg and the top of obstacle when the leading leg just passed over the obstacle. The VD of the trailing leg was determined as the vertical distance between the toe of the trailing leg and the top of obstacle when the trailing leg just passed over the obstacle. Walking velocity was assessed when stepping over the first and the second obstacle. All kinematic data above, except for walking velocity, were normalized by leg length to avoid a possible confounding effect of leg length. FIPs of the leading and trailing leg were measured by Zeno walkway system (0.8 m x 6 m active area, ProtoKinetics, Havertown, PA, USA), and were normalized by body weight.

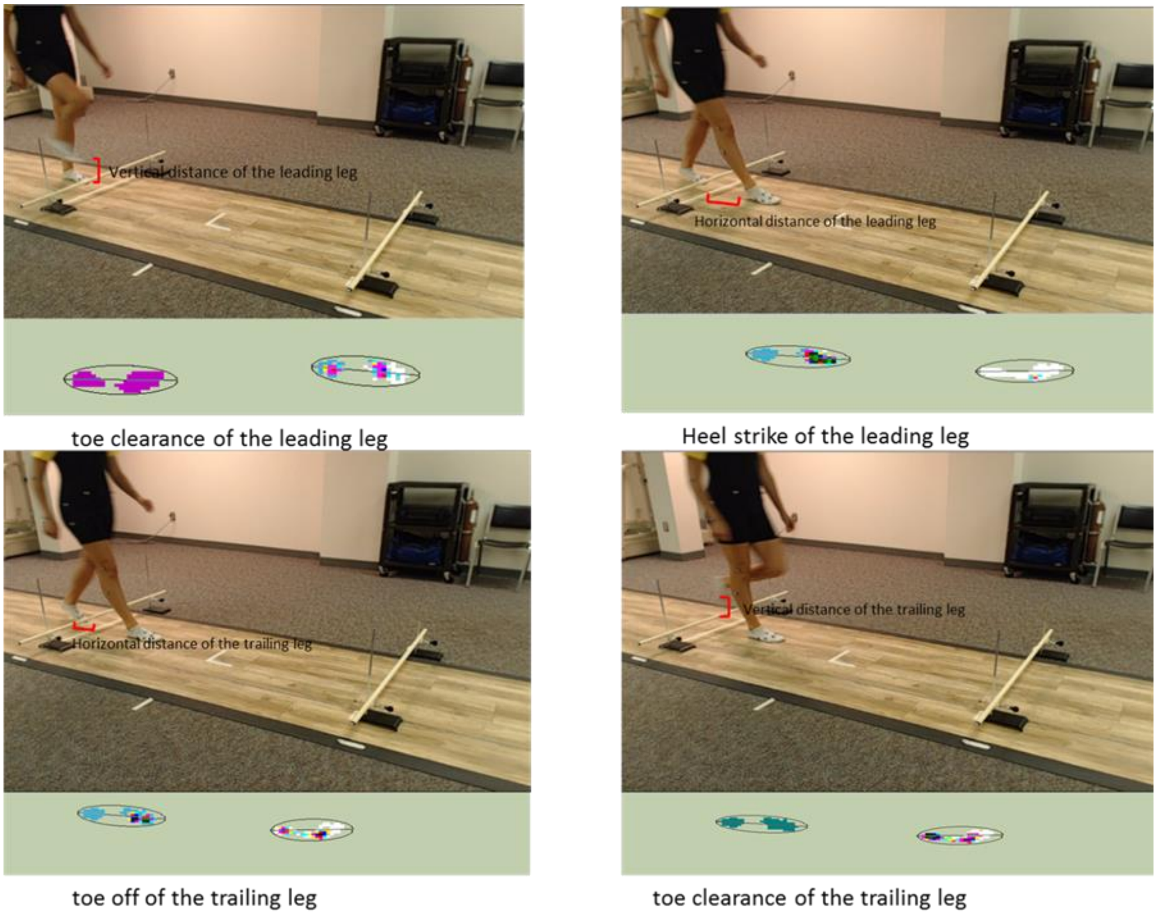

Figure 1. Illustration of spatiotemporal kinematic parameters and foot integrated pressure (colored footprint at the bottom of the figure).

Experimental protocol

After screening for inclusion/exclusion criteria, informed consent was obtained from participants. Participants were asked to walk at their normal walking speed on the 6-meter walkway for 5 times to calculate their average step length and preferred walking speed. The calculated step length was used to determine the placement of the first obstacle as well as the interval between two obstacles. The first obstacle was set three steps away from the starting point. And the second obstacle was set one, two, or three steps away based on the trial condition. There were 3 different interval conditions: one-step, two-step, and three-step, and each condition had 5 repetitions (Figure 2). Thus, a total of 15 trials were randomly assigned to participants. In order to obtain the natural obstacle negotiation strategy, participants were allowed to choose their preferred walking speed and choose which leg they preferred to lead. HD, VD, and FIPs of the leading and trailing leg were computed to compare obstacle avoidance strategy. The foot integrated area of both legs as well as the walking velocity when stepping over the first and second obstacle were also recorded. All kinematic parameters were determined using the custom MATLAB R2011a program (MathWorks, Natick, MA).

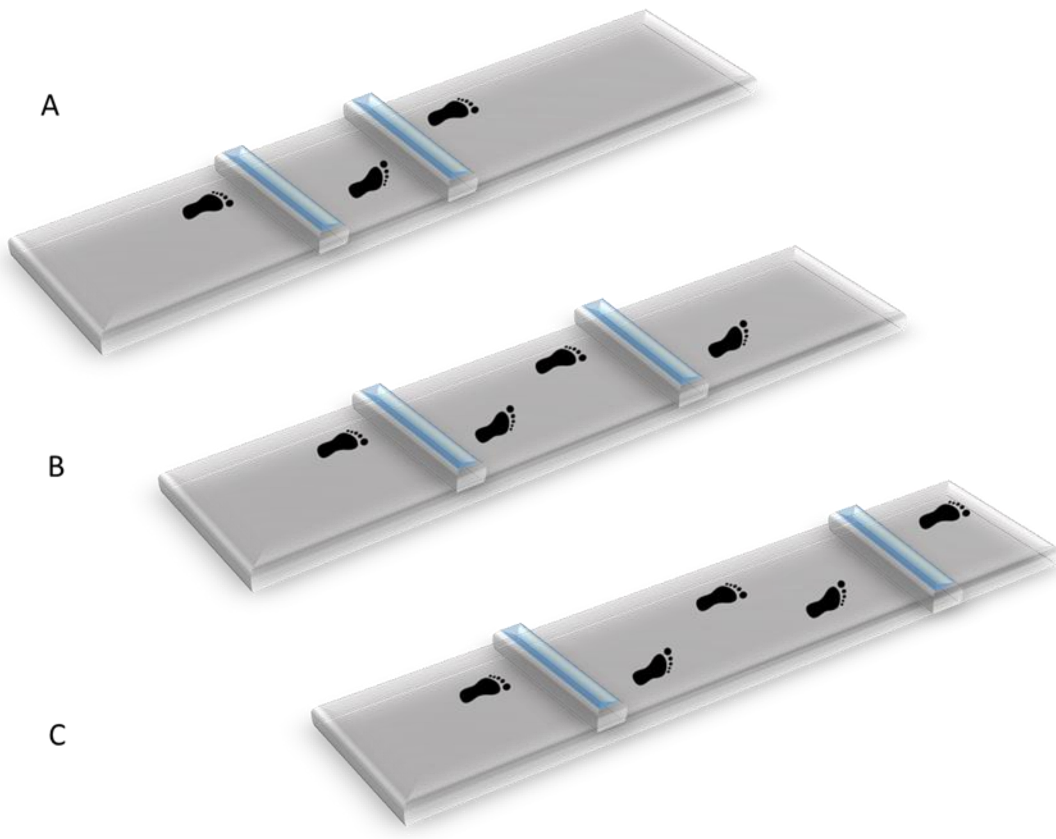

Figure 2. Experimental diagram. Three different intervals between two obstacles: One step interval (A), two-step interval (B), and three-step interval (C)

Statistical analysis

All data collected were normally distributed based on observation on QQ-plots. A three-way repeated measures ANOVA was used to calculate the effect the legs (leading vs. trailing), intervals (one-step vs. two-step vs. three-step), and obstacles (first vs. second) as well as their interactions on the parameters of foot integrated area, walking velocity, HD, VD, and FIP. If ANOVA revealed a significant interaction, a post-hoc pairwise comparison with Tukey correction was used. A Pearson correlation was used to explore the relationship between the VD/HD and FIP when stepping over obstacles. The level of significance was set at 0.05. All statistical analysis were completed in SPSS 18.0 (IBM Corporation, Armond, NY). Partial eta square method was used to measure the effect size.

Chapter 3. Results

All participants were able to complete all tasks without tripping or falling. Partial eta squared value was 0.630 for FIP, 0.334 for HD, and 0.383 for VD, showing a large effect size in current study (Richardson, 2011).

The correlations between FIP and HD/VD showed that at the second obstacle, when the interval was two-step or three-step away, there were moderate correlations between FIP and leading leg HD, trailing leg HD as well as leading leg VD. Also, a moderate correlation was found between FIP and leading Leg VD at the first obstacle when the interval was one-step away (Table 2).

Table 2. The correlation between foot integrated pressure (FIP) and kinematic gait parameters of horizontal distance (HD)/vertical distance (VD) at obstacle 1 and at obstacle 2. Significant results were marked as bold. Positive R-value: positive correlation. Negative R-value: negative correlation.

			Leading leg HD	Trailing leg HD	Leading leg VD	Trailing leg VD
FIP	Obstacle 1	One-step	R = 0.271; p = 0.308	R = -0.437; p = 0.061	**R = 0.550; p = 0.015**	R = 0.004; p = 0.986
		Two-step	R = 0.252; p = 0.399	R = -0.357; p = 0.134	R = 0.236; p = 0.332	R = 0.020; p = 0.936
		Three-step	R = 0.172; p = 0.482	R = -0.329; p = 0.169	R = 0.147; p = 0.549	R = 0.102; p = 0.667
	Obstacle 2	One-step	R = 0.307; p = 0.202	R = -0.298; p = 0.216	R = 0.280; p = 0.91	R = 0.112; p = 0.649
		Two-step	**R = 0.707; p = 0.001**	**R= - 0.456; p = 0.05**	**R = 0.443; p = 0.05**	R = 0.040; p = 0.872
		Three-step	**R = 0.538; p = 0.018**	**R = -0.427; p = 0.048**	**R = 0.595; p = 0.007**	R = 0.077; p = 0.755

Three-way repeated measures ANOVA revealed significant interactions among the effect of different legs, different intervals, and different obstacles on foot integrated areas ($F_{2, 36} = 7.44$; $p = 0.002$), on walking speed ($F_{2, 36} = 8.16$; $p = 0.001$), on FIP ($F_{2, 36} = 30.66$; $p < 0.0001$), on HD ($F_{2,36} = 9.01$; $p = 0.001$), and on VD ($F_{2,36} = 11.15$; $p < 0.0001$).

Post-hoc comparison showed different results when stepping over the first obstacle compared to the second obstacle. The detailed results are reported in the two following sections.

Stepping over the first obstacle

When the interval was one-step, the foot integrated area of leading leg was significantly larger than the one of trailing leg (Figure 3, $p < 0.01$). The walking velocity of the leading leg was significantly lower compared to the trailing leg (Figure 4, $p < 0.01$). While there was no significant difference in HD between the leading leg and trailing leg, the FIP and VD of the leading leg was higher than the trailing leg (Figure 5, $p <0.001$; Figure 7, $p <0.05$).

When the intervals were at two- and three-step conditions, post-hoc comparisons showed no differences in foot integrated area, FIP, and HD between the leading leg and trailing leg. However, a significant slower walking velocity (Figure 4, $p < 0.001$ for both two-step and three-step conditions) and higher VD (Fig. 7, $p < 0.05$ for both two-step and three-step conditions) were found in the leading leg compared to the trailing leg.

Stepping over the second obstacle

When stepping over the second obstacle, the foot integrated area was significantly smaller for both legs when the interval was two-step (Figure 3, $p < 0.05$ for the leading leg; $p < 0.001$ for the trailing leg) and three-step (Figure 3, $p < 0.05$ for the leading leg; $p < 0.01$ for the trailing leg) compared to the first obstacle. However, when the interval was one-step, the foot integrated area in the leading leg was smaller (Figure 3, $p < 0.05$) while the foot integrated area of trailing leg was larger (Figure 3, $p < 0.01$) when stepping over the second obstacle compared to the first one.

For walking velocity, regardless of the interval conditions, the walking velocity was higher when stepping over the second obstacle than stepping over the first obstacle in both the leading and trailing legs (Figure 4).

There was no significant difference in leading leg FIP between the first and second obstacle when the interval was one-step. However, the FIP of the leading leg was significantly higher when stepping over the second obstacle compared to the first obstacle when the interval was two-step (Figure 5, $p < 0.05$) and three-step (Figure 5, $p < 0.01$). Also, the FIP in the leading leg was significantly higher than the trailing leg when stepping over the second obstacle at the two-step interval (Figure 5, $p < 0.001$) and the three-step interval (Figure 5, $p < 0.001$).

The HD of the leading leg was significantly longer when stepping over the second obstacle compared to the first one at one-step (Figure 6, $p < 0.001$), two-step (Figure 6, $p < 0.001$) as well as three-step intervals (Figure 6, $p < 0.001$). On the contrary, the HD of the trailing was shorter when stepping over the second obstacle in comparison to the first obstacle in all interval conditions (Figure 6, $p < 0.05$ for one-step, $p < 0.001$ for two-step, $p < 0.001$ for three-step).

When the interval was one-step, the VD of the trailing leg was significantly higher when stepping over the second obstacle compared to stepping over the first one (Figure 7, $p < 0.05$). However, when the interval between the obstacles was three-step, the VD of the trailing leg was lower when stepping over the second obstacle than the first obstacle (Figure 7, $p < 0.05$)

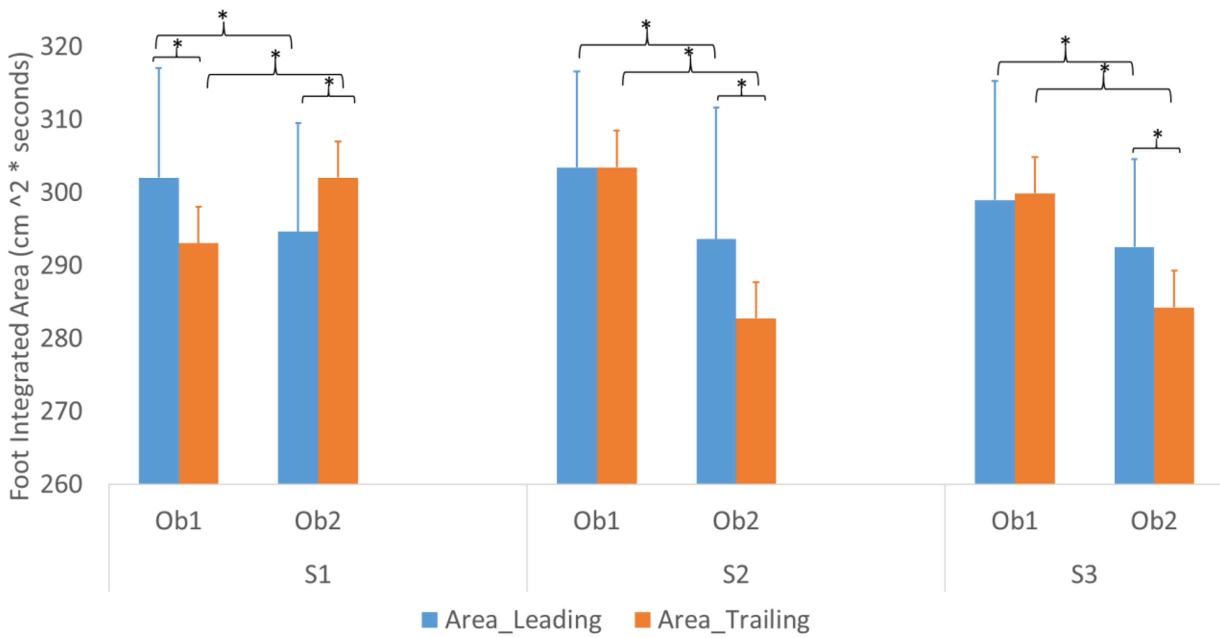

Figure 3. Foot integrated area in the leading leg (blue-colored) **and trailing leg** (orange-colored). S1: one-step interval; S2: two-step interval; S3: three-step interval; Ob1: first obstacle; Ob2: second obstacle. * indicates significant difference between two parameters. ($p < 0.05$)

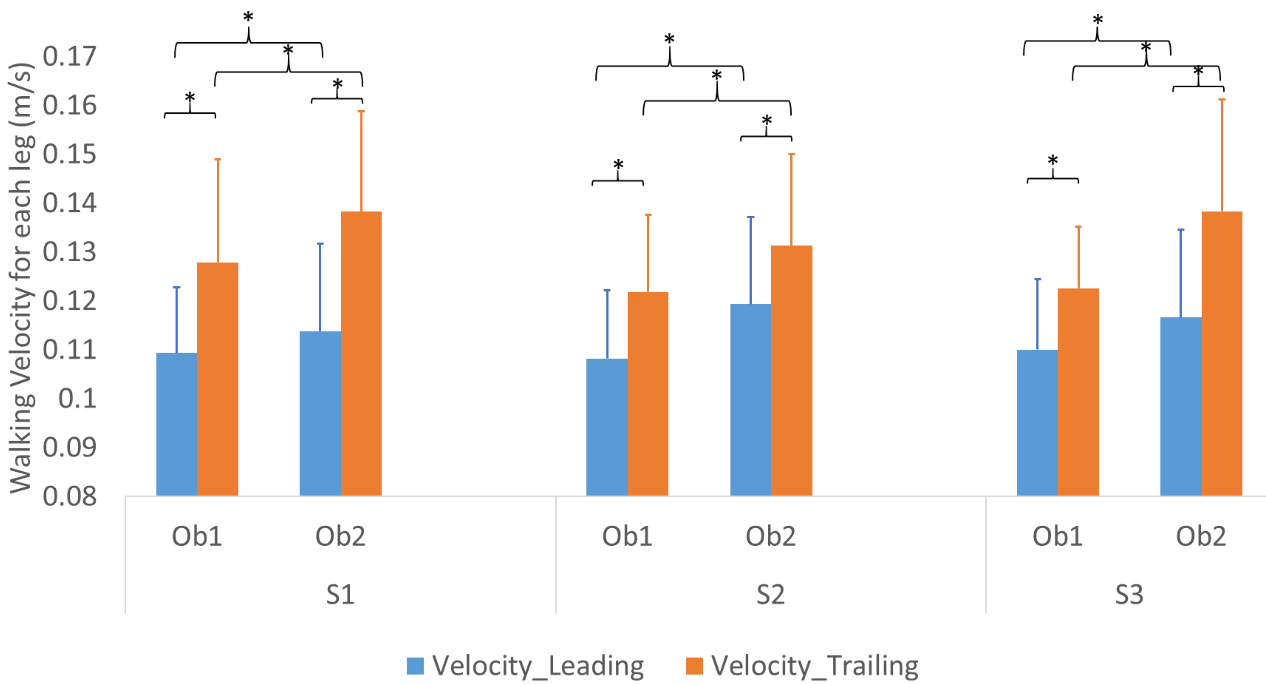

Figure 4. Walking velocity in the leading leg (blue-colored) **and trailing leg** (orange-colored)**.** S1: one-step interval; S2: two-step interval; S3: three-step interval; Ob1: first obstacle; Ob2: second obstacle. * indicates significant difference between two parameters. ($p < 0.05$)

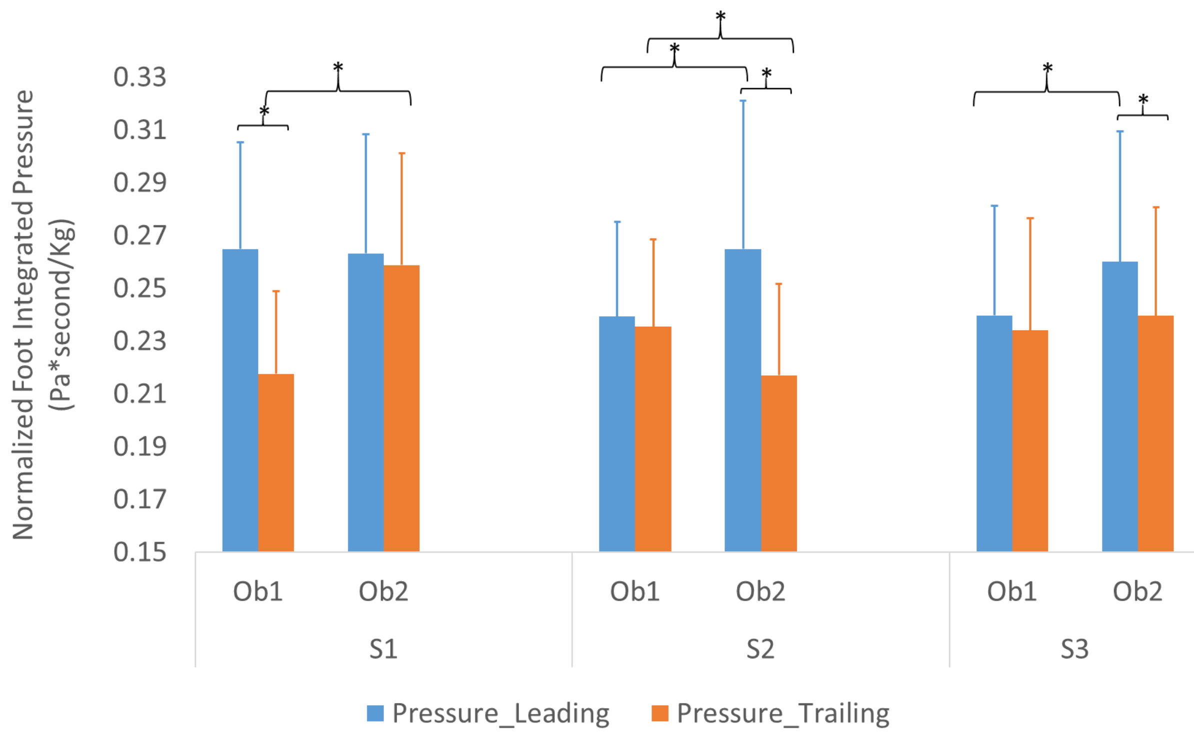

Figure 5. Foot integrated pressure (FIP) in the leading leg (blue-colored) **and trailing leg** (orange-colored) **were normalized by body weight.** S1: one-step interval; S2: two-step interval; S3: three-step interval; Ob1: first obstacle; Ob2: second obstacle. * indicates significant difference between two parameters. ($p < 0.05$)

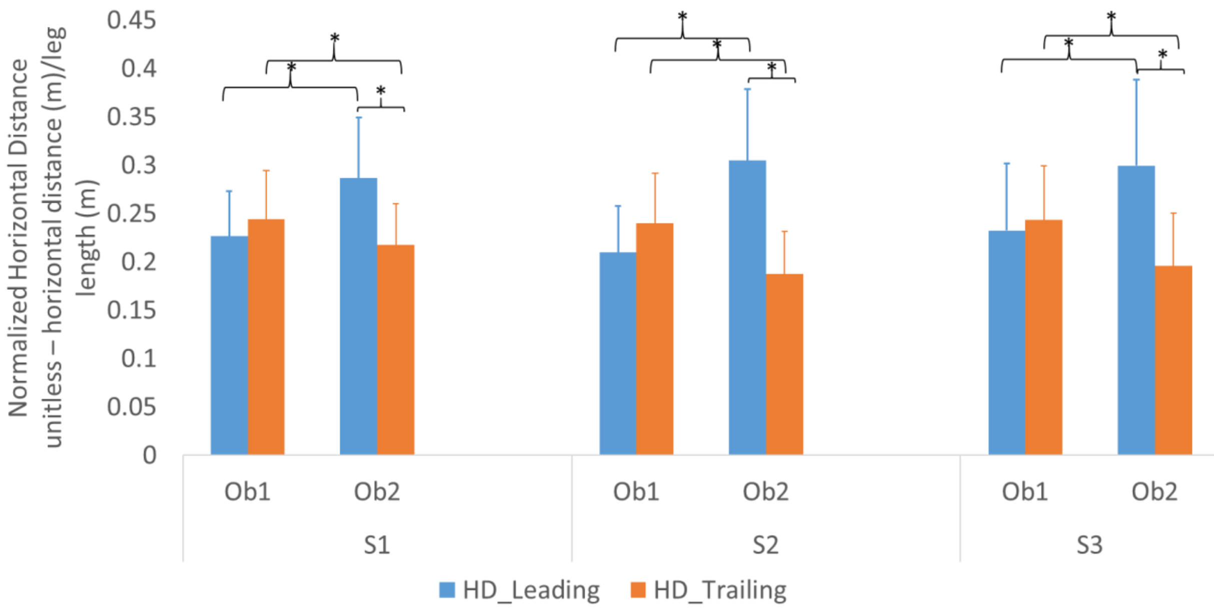

Figure 6. Normalized horizontal distance (HD) of the leading leg (blue-colored, horizontal distance between the heel of the leading leg and the obstacle when the leading leg' heel contacted the ground) **and the trailing leg** (orange-colored, horizontal distance between the toe of the trailing leg and the obstacle when the trailing leg's toe pushed off the ground). S1: one-step interval; S2: two-step interval; S3: three-step interval; Ob1: first obstacle; Ob2: second obstacle. * indicates significant difference between two parameters. ($p < 0.05$)

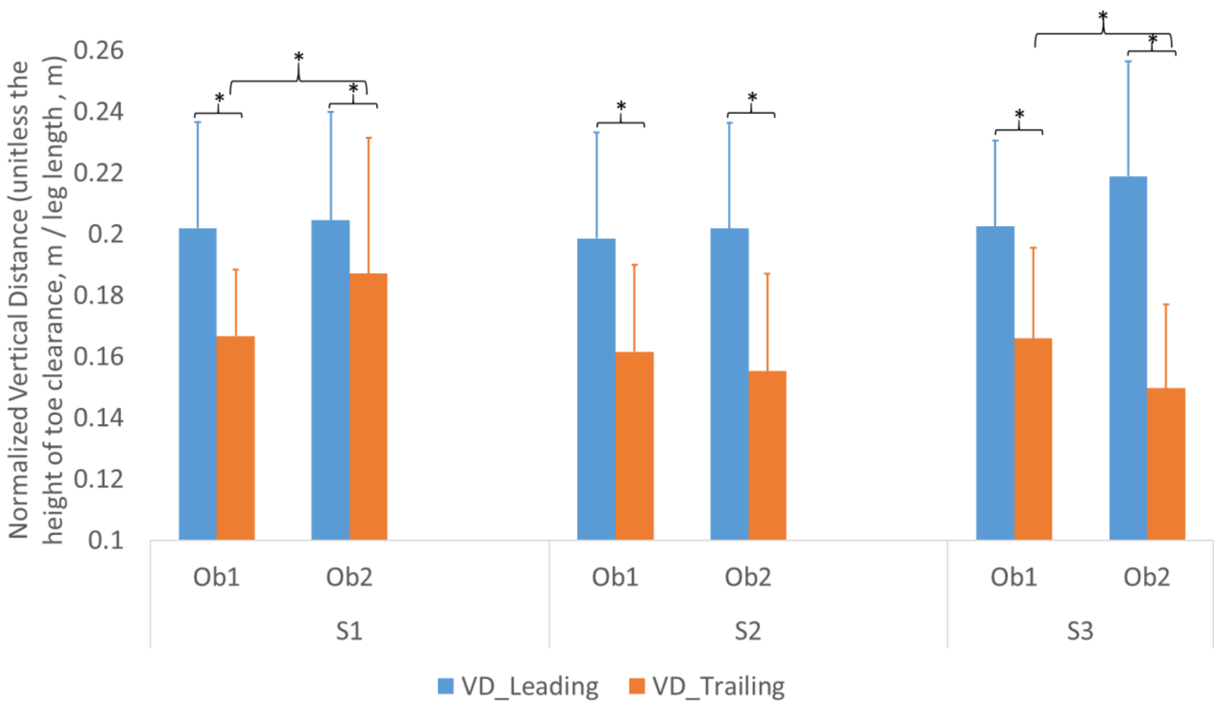

Figure 7. Normalized vertical distance (VD) of the leading leg (blue-colored, vertical distance between the toe of the leading leg and the top of obstacle when the leading leg just passed over the obstacle) **and the trailing leg** (orange-colored, vertical distance between the toe of the trailing leg and the top of obstacle when the trailing leg just passed over the obstacle). S1: one-step interval; S2: two-step interval; S3: three-step interval; Ob1: first obstacle; Ob2: second obstacle. * indicates significant difference between two parameters. ($p < 0.05$)

Chapter 4. Discussion

This study attempted to explore the strategies of double obstacle crossing when the intervals between obstacles were different. The results showed that the FIP in the leading leg was higher, HD of the leading leg was longer, VD of the trailing leg was lower, and the foot integrated area of the leading leg was smaller when stepping over the second obstacle compared to the first obstacle. These results supported my research hypotheses and suggested that the presence of the second obstacle would induce significant differences in FIP and kinematic parameters when stepping over the second obstacle regardless of whether the interval was one-step, two-step, or three-step in healthy young adults. These findings were consistent with a previous study (Chien et al., 2018). In their study, they found when the interval between two obstacles was three-steps away, the toe clearance was higher when stepping over the second obstacle than stepping over the first one. They also found the HD of the leading leg was significantly higher at the second obstacle in comparison with the first obstacle in young adults. The specific strategies young adults used to step over the first and second obstacle were discussed in detail below.

<u>Stepping over the first obstacle</u>

FIP was significantly higher in the leading leg compared to the trailing leg when the interval was one step away. It was speculated when the interval was only one step away, the trailing leg of the first obstacle acted as the leading leg to step over the second obstacle as well because there was no extra step could be taken. Therefore, as the trailing leg spent more time in the swing phase to step over two obstacles, the leading leg, on the contrary, would spend more in stance phase. This increased support time contributed to the higher FIP of the leading leg.

When the interval was two or three steps away, the situation was totally different. No significant differences were found in FIP between the leading and trailing leg when the interval was two or three steps away. Meanwhile, the foot integrated area and HD of both legs showed no significant difference. The only difference was the VD where the VD of the leading leg was higher compared to the trailing leg. A possible explanation for this difference was based on the somatosensory information transfer concept (Hedel et al., 2002; Chien et al., 2018). As the leading leg passed through the obstacle, it transferred the information about size and height of the obstacle to the trailing leg. Therefore, the trailing leg decreased the height of toe clearance because of this transfer effect for energy conservation.

In the two-step and three-step conditions, the foot integrated areas of the leading and trailing leg were equal. Thus, FIP can be used as an indicator for efficiency. Despite of the VD difference, the same FIP of the leading and the trailing leg inferred that the efficiency of obstacle crossing still existed when stepping over the first obstacle. Similar to impulse ((Bovonsunthonchai et al., 2015), the efficient strategy adjusted the kinematic gait parameters to make the leading and trailing leg contribute equal FIP when stepping over the first obstacle.

Stepping over the second obstacle

FIP of the leading leg was significantly higher at the second obstacle compared to the first obstacle when the interval was two steps and three steps. This increase in FIP was consistent with foot integrated area. Based on the formula of pressure, the smaller the area is, the higher the pressure would be. The decreased foot integrated area in the leading leg helped explain the increase in the FIP.

Meanwhile, at the second obstacle, the FIP was significantly higher in the leading leg compared to the trailing leg when the interval was two and three steps away. These changes might be attributed to the differences in spatiotemporal gait parameter. The VD and HD of the leading leg were both higher/longer in the leading leg than the trailing leg. These kinematic changes made the leading leg to contribute a higher FIP when stepping over the obstacle. Also, the moderate correlation between FIP and VD/HD supported this explanation. (Table 2). To be noted, the increased HD and VD of the leading leg as well as the decreased HD of the trailing leg were considered as a conservative strategy to avoid tripping (Galna et al., 2009). They conducted a systematic review and concluded that older adults would use a more conservative strategy to step over an obstacle. The findings from their review suggested greater hip flexion during the swing phase, which contributed to a higher VD in the leading leg.

Moreover, Chou and Draganich (1998) found when young adults reduced the HD of the trailing leg, the swing time of the trailing leg from toe off to cross over the obstacle was decreased as well. This reduction in time resulted in decreased hip flexion, decreased knee flexion, and decreased ankle dorsiflexion of the trailing leg, which contributed to the decreased VD in the trailing leg. And this was also observed in current study. In accordance with these two studies (Galna et al., 2009; Chou and Draganich, 1998), the results showed when stepping over the second obstacle, young adults would intend to use a more cautious and conservation strategy. This means although no individual tripped over the obstacle, the presence of second obstacle could still induce a potential challenge to young adults.

Another way to explain the different strategies when stepping over the second obstacle and the first obstacle is related to walking velocity. In this study, participants tended to cross over the second obstacle quicker than the first obstacle. This phenomenon is consistent with the concepts of vision pre-programming and somatosensory information transfer as proposed by previous researchers. As suggested by Palta and Vickers (2003), individuals would fixate on the area two steps ahead to allow them sufficient time to adjust their gait. When the interval was two steps away, participants used visual input to proactively determine and readjust the strategy for stepping over the second obstacle after crossing over the first one. This adjustment was supported by the finding that the HD of the leading leg was significantly higher when stepping over the second obstacle compared to the first obstacle regardless of the interval was one, two, or three steps away.

The findings of this study were consistent with the concept of somatosensory information transfer (Hedel et al., 2002; Chien et al., 2018). When the interval was two-step, participants used the same leg to step over two obstacles. While for the three-step interval condition, individuals would use a different leg to cross over two obstacles (Figure.2C). The significant differences in both two-step and three-step conditions supported that the transfer effect could happen to the same leg as well as to the opposite leg. As for the decreased HD of the trailing leg, though it was considered as a conservative strategy, it is possible that healthy young adults chose to be closer to the second obstacle so that they could lift the leading leg higher and longer to pass the obstacle faster. The faster movement at the second obstacle required the leading leg to use more force to brake and stabilize and an increased FIP was observed as a result. The result of walking velocity supported this explanation by showing increased walking velocity in both legs when stepping over the second obstacle compared to stepping over the first obstacle in all interval conditions. The significant difference of FIP between the leading leg and the trailing leg showed the strategy of stepping over the second obstacle was inefficient based on previous studies. (Huang and Kuo, 2014; Bovonsunthonchai et al., 2015). This inefficiency regarding FIP might indicate more energy consumption by individuals during obstacles negotiation. Regardless of the strategies used by the individuals to cross the obstacles when intervals differed, the clinical importance is the ability to negotiate obstacles without tripping or falling. Healthy young adults in our study were able to negotiate obstacles successfully, though the strategy might be inefficient energetically based on FIP analyses.

Conclusion

This study provided information about the basic mechanism of multiple obstacles negotiation in a population of health young adults. To summarize, this study suggested that the presence of a second obstacle changed the strategy of obstacle negotiation regardless of whether the intervals were one, two, or three steps away. Young individuals potentially learned information about the obstacle from vision and somatosensory systems, and they tended to cross over the second obstacle faster. Based upon our findings when investigating FIP of the leading and trailing legs, our participants appeared to use an inefficient strategy to step over the second obstacle, which may imply that the presence of a second obstacle was more challenging even for healthy young adults.

Limitations

There were some limitations in current study. First of all, convenience sampling was used in this study. Participant were students at University of Nebraska Medical Center, and most of them were physical therapy students. They were in their early to mid-twenties and were more active compared to the general population of young individuals, and as such, might induce a potential threat to the external validity. Small sample size was another limitation for this study; however, partial eta squared values were 0.630 for FIP, 0.334 for HD, and 0.383 for VD, showing a large effect size. Moreover, the current study did not consider the effect of the changing sides of the leading leg. Some individuals may use one leg to start in some trials, and switch to another leg to start in other trials. Failing to include the effect of changing of the crossing leg between trials might influence the results of study. The strategy of leading with dominant leg or non-dominant leg might be different; however, of clinical relevance is no one tripped or fell in the study. Last but not the least, as vision plays a huge role in the strategy of obstacle negotiation, a visual acuity screening test should have been performed to ensure participants had accurate visual input. Participants' lacking a visual acuity or input might affect their ability of visual guidance during obstacle negotiation process.

Future directions

In the future, obstacles with different heights could be used in study design. Multiple studies have suggested that obstacle height would affect the strategy of obstacle negotiation (Park and Lee, 2012; Bovonsunthonchai et al., 2015; Chou and Draganich, 1998). Using obstacles with different heights can help us better understand the mechanism of obstacle negotiation. A visual acuity test should be added to the inclusion/exclusion criteria to assess if participants have normal visual acuity with correction and normal central and peripheral visual fields. The experimental protocol could be modified to require each participant to start with their dominant legs in all trials to eliminate the effect of the crossing leg change. As compared to Zeno walkway used in this study, a more reliable and validated tool, such as multiple fixed force plates that are long enough to allow measurement in one trial for different interval conditions, could be chosen to conduct the study.

Moreover, this study could be expanded to older adults or other patient populations. There was a study showing that training of stepping over multiple obstacles could significantly increase the walking speed for patients after stroke (Jaffe et al., 2004). However, the mechanism behind the training effect is still unknown. By comparing the differences in strategies between other patient populations and healthy young adults, we might be able to better understand how aging or pathologies might change human locomotion in obstacle negotiation, and potentially inform clinical interventions to improve patient safety when crossing obstacles.

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