MEDICAL SCIENCE MONITOR

CLINICAL RESEARCH

e-ISSN 1643-3750
© Med Sci Monit, 2015; 21: 2041-2049
DOI: 10.12659/MSM.893965

Received: 2015.02.27
Accepted: 2015.04.02
Published: 2015.07.14

Ground Reaction Forces of the Lead and Trail Limbs when Stepping Over an Obstacle

Authors' Contribution:
Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
Literature Search F
Funds Collection G

ABCDEF **Sunee Bovonsunthonchai**
BF **Fuengfa Khobkhun**
ACD **Roongtiwa Vachalathiti**

Faculty of Physical Therapy, Mahidol University, Nakhon Pathom, Thailand

Corresponding Author: Sunee Bovonsunthonchai, e-mail: sunee.bov@mahidol.ac.th

Source of support: Departmental sources

Background: Precise force generation and absorption during stepping over different obstacles need to be quantified for task accomplishment. This study aimed to quantify how the lead limb (LL) and trail limb (TL) generate and absorb forces while stepping over obstacle of various heights.

Material/Methods: Thirteen healthy young women participated in the study. Force data were collected from 2 force plates when participants stepped over obstacles. Two limbs (right LL and left TL) and 4 conditions of stepping (no obstacle, stepping over 5 cm, 20 cm, and 30 cm obstacle heights) were tested for main effect and interaction effect by 2-way ANOVA. Paired *t*-test and 1-way repeated-measure ANOVA were used to compare differences of variables between limbs and among stepping conditions, respectively. The main effects on the limb were found in first peak vertical force, minimum vertical force, propulsive peak force, and propulsive impulse.

Results: Significant main effects of condition were found in time to minimum force, time to the second peak force, time to propulsive peak force, first peak vertical force, braking peak force, propulsive peak force, vertical impulse, braking impulse, and propulsive impulse. Interaction effects of limb and condition were found in first peak vertical force, propulsive peak force, braking impulse, and propulsive impulse.

Conclusions: Adaptations of force generation in the LL and TL were found to involve adaptability to altered external environment during stepping in healthy young adults.

MeSH Keywords: **Locomotion • Lower Extremity • Observational Study • Young Adult**

Full-text PDF: http://www.medscimonit.com/abstract/index/idArt/893965

2345 2 5 24

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS] [Index Copernicus]

Background

Tripping during locomotion can be caused of falls in older adults. Falls often occur without prior warning sign [1] and are a major cause of morbidity and mortality [2]. The ability to accomplish obstacle negotiation is essential for independent mobility, which requires proper adaptive locomotor responses to optimize the step and good single-leg balance maintenance [3]. Difficulty with obstacles is especially common in the elderly and persons with pathology [4–9]. Understanding the kinematic and kinetic data when stepping over obstacles will provide useful information for training of persons with ambulatory limitations [4–6,10]. To step over an obstacle, there must be balance control of the supporting limb and increased lifting of the lead leg as it steps over the obstacle [11]. Successful obstacle stepping requires precise and sequential limb movements. The lead limb (LL) must first cross the obstacle, followed by the trail limb (TL). A report has indicated that individuals sometimes have difficulty controlling the movement in the TL due to loss of visual feedback [12]. Lower limb trajectory over an obstacle is updated by concurrent lower visual field information [13]. Visible properties of the obstacle such as different widths and heights were used for altering gait pattern and leg movement to avoid or accommodate obstacles [14].

The TL has a shorter time and lesser distance for safe preparation to step with appropriate clearance. Lesser toe clearance of the TL was presented when compared to the LL and it may lead to tripping and falling [15,16]. Adaptive movement characteristics automatically occur in healthy young adults when confronted with altered environmental situations and trip perturbations [15,17,18]. Obstacle stepping performance may be expressed in terms of kinematic behaviors such as movement control of the limbs, toe clearance quality, and stepping time [9,12,15,16].

The contribution of kinetic characteristics is often used to explain the process of gait [10] and locomotion [19] control. Patterns of force generation/absorption and their related time help us understand the adaptive mechanisms needed for proper and safe movement control [19,20]. Therefore, the purpose of this study was to monitor how the LL and TL forces are modulated when stepping over obstacles of various heights, as well as to determine the contribution of kinetic data to understanding normal mechanism control in young adults.

Material and Methods

Participant

Thirteen healthy young women participated in the study. Average age was 20.5±1.33 years, average weight was 52.5±3.66 kg, and average height was 158.7±31.1 cm. The subjects were free from any diseases that impede mobility and had no deficits of vision, hearing, or balance control. Prior to participation, all participants signed informed consent approving by University Research Review Board (MU-IRB 2012/093.0210).

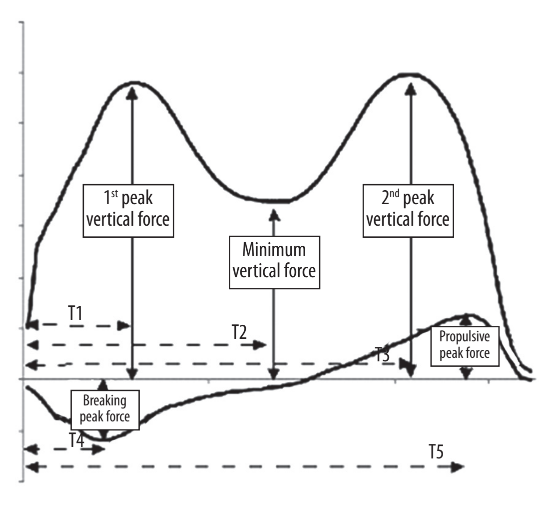

Figure 1. Ground reaction forces (GRFs) data included the vertical force (first peak vertical force, minimum vertical force, and second peak vertical force), the anteroposterior force (braking peak force and propulsive peak force), and time to peak force (first peak vertical force (T1), time to minimum force (T2), time to second peak vertical force (T3), time to braking peak force (T4), and time to propulsive peak force (T5).

Procedure

Participants walked along an 8-meter walkway at a comfortable gait speed and stepped over obstacle boxes (5 cm in width and 80 cm in length) of different heights: 5 cm, 20 cm, and 30 cm. The boxes were placed between 2 force plates (Advanced Mechanical Technologies, Boston, MA series OR-067). Force parameters during walking over the obstacle were collected for the LL and TL at 1000 Hz.

Data analysis

GRFs data included time to the first peak force, time to minimum force, time to the second peak force, time to braking peak force, time to propulsive peak force, first peak vertical force, minimum vertical force, second peak vertical force, braking peak force, propulsive peak force, vertical impulse, braking impulse, and propulsive impulse (Figure 1). GRFs were normalized by body weight (BW) and reported as %BW. Time to the peak forces were reported in seconds. Impulses were calculated by the following equation and were reported as Ns/BW;

$$\text{Impulse} = \Delta\text{t}\left(\sum_{i=0}^{n}\text{F}i\right)$$

Force data were selected when each foot contacted the force plate and were filtered by the Woltring routine method. Three walking trials were collected and 1 successful trial was used for analyses.

Statistical analysis

A power analysis testing by G*Power statistical software version 3.1.9.2 was performed beyond the data of 5 participants. Priori test to compute the required sample size for 1-way repeated measure was performed. Required range of sample sizes to find a statistically significant difference among conditions in almost GRFs variables with a type 1 error of 0.05 and a power of 0.90 were 2 and 12, except for time to the first peak force of lead limb, second peak vertical force of lead limb, and time to braking peak force of trail limb, which required more than 30 samples. Thus, 13 volunteer participants were recruited in the study.

All data were analyzed by SPSS version 16.0 and demonstrated normal distribution tested by Kolmogorov-Smirnov goodness of fit test. Two limbs (right or LL and left or TL) and 4 conditions of walking (no obstacle, crossing over 5 cm, 20 cm, and 30 cm obstacle heights) were tested for the main effect and interaction effect by 2-way ANOVA. Paired t-test and 1-way repeated-measures ANOVA were used to compare the differences of force variables between limbs and among walking conditions. LSD was used to find differences among conditions.

Results

Main effect and interaction effect of limbs and conditions

Two-way ANOVA demonstrated the main effects of limb in first peak vertical force [F (1, 96)=5.523, p=0.021], minimum vertical force [F (1, 96)=9.982, p=0.002], propulsive peak force [F (1, 96)=11.477, p=0.001], and propulsive impulse [F (1, 96)=38.965, p<0.001].

Main effects of condition were demonstrated in time to minimum force [F (3, 96)=12.420, p<0.001], time to the second peak force [F (3, 96)=41.087, p<0.001], time to propulsive peak force [F (3, 96)=30.601, p<0.001], first peak vertical force [F (3, 96)=5.984, p=0.001], braking peak force [F (3, 96)=10.229, p<0.001], propulsive peak force [F (3, 96)=11.233, p<0.001], vertical impulse [F (3, 96)=21.966, p<0.001], braking impulse [F (3, 96)=18.498, p<0.001], and propulsive impulse [F (3, 96)=36.255, p<0.001].

Interaction effects of limb and condition were found in first peak vertical force [F (3, 96)=3.129, p=0.029], propulsive peak force [F (3, 96)=4.905, p=0.003], braking impulse [F (3, 96)=13.44, p<0.001], and propulsive impulse [F (3, 96)=10.94, p<0.001].

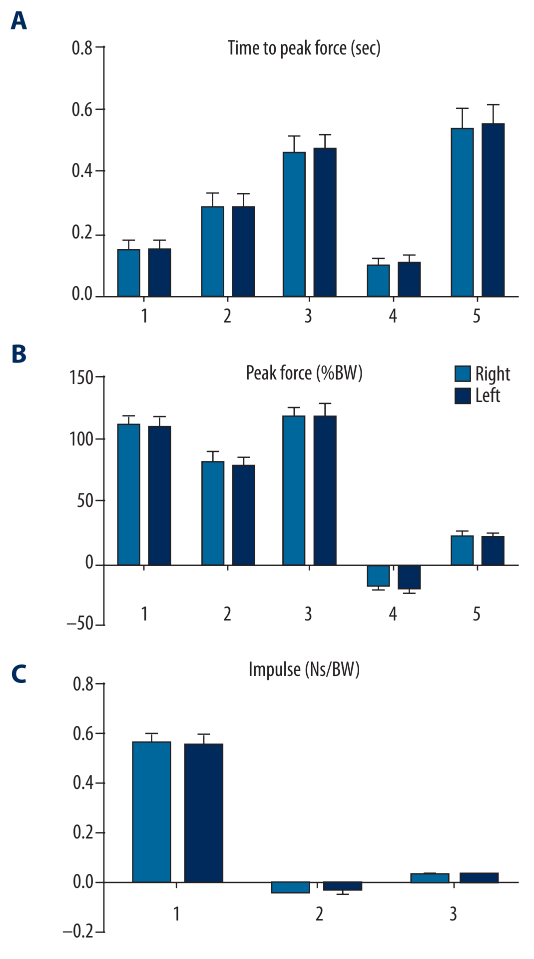

Figure 2. Comparisons of the variables [(**A**) 1) Time to the first peak force, 2) Time to minimum force, 3) Time to the second peak force, 4) Time to braking peak force, and 5) Time to propulsive peak force, (**B**) 1) First peak vertical force, 2) Minimum vertical force, 3) Second peak vertical force, 4) Braking peak force, and 5) Propulsive peak force, and (**C**) 1) Vertical impulse, 2) Braking impulse, and 3) Propulsive impulse] between the right and left limbs during no obstacle walking condition (n=13), significant difference tested by paired t-test at p<0.05.

Comparisons of force variables between limbs in each walking condition

In each condition of obstacle crossing, the paired t-test was used to compare the variables between sides. No significant difference between the left and right sides was found when walking in the no obstacle condition (Figure 2). When crossing the 5 cm obstacle height, there were significant differences of time to the second peak force (p=0.001) and time to propulsive peak force (p=0.002) between LL and TL (Figure 3). When crossing the 20-cm obstacle height, significant differences

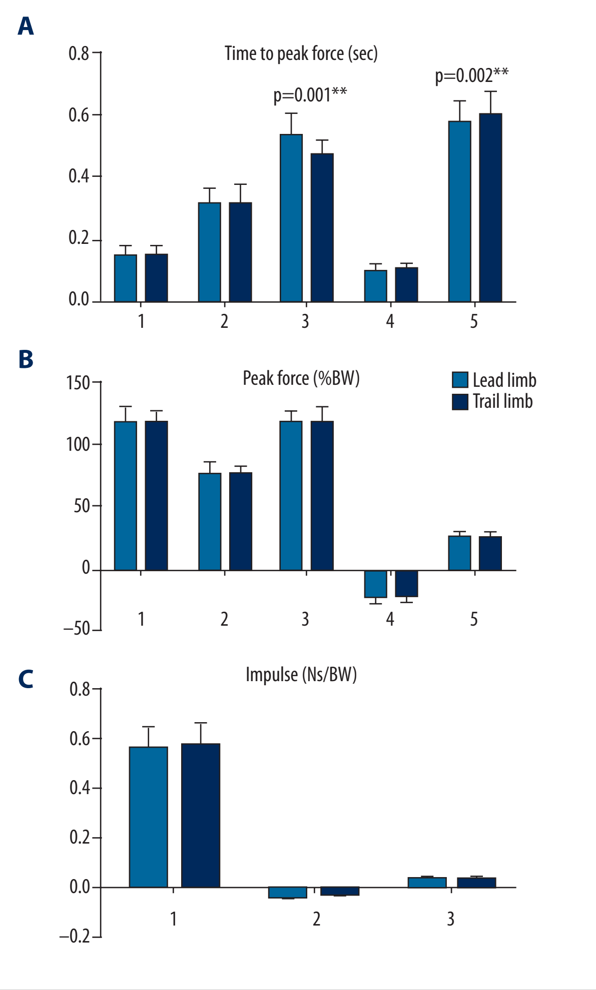

Figure 3. Comparisons of the variables [(**A**) 1) Time to the first peak force, 2) Time to minimum force, 3) Time to the second peak force, 4) Time to braking peak force, and 5) Time to propulsive peak force, (**B**) 1) First peak vertical force, 2) Minimum vertical force, 3) Second peak vertical force, 4) Braking peak force, and 5) Propulsive peak force, and (**C**) 1) Vertical impulse, 2) Braking impulse, and 3) Propulsive impulse] between the lead limb and trail limb during obstacle crossing over 5 cm obstacle height condition (n=13), significant difference tested by paired *t*-test at *p*<0.05.

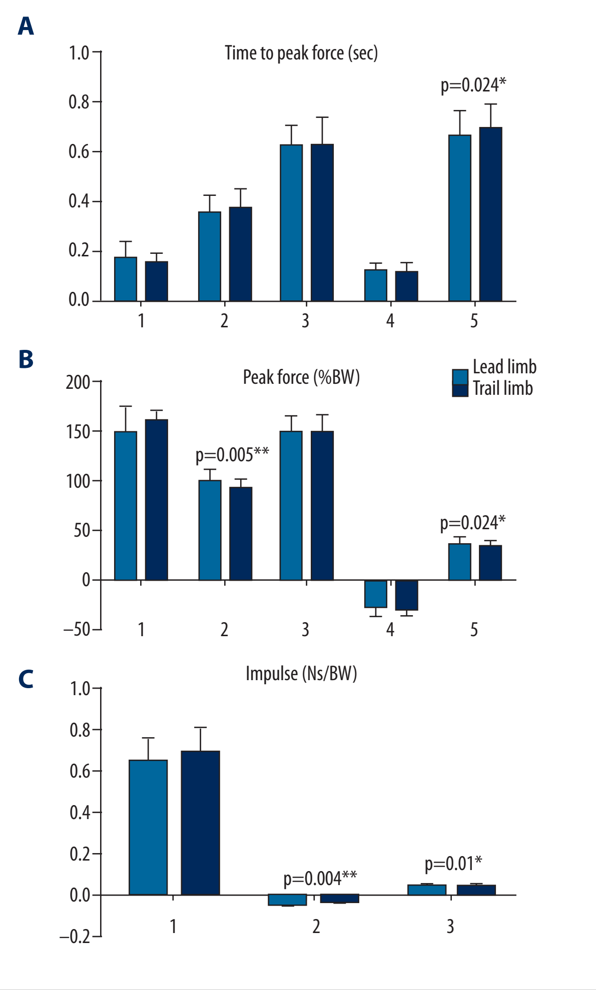

Figure 4. Comparisons of the variables [(**A**) 1) Time to the first peak force, 2) Time to minimum force, 3) Time to the second peak force, 4) Time to braking peak force, and 5) Time to propulsive peak force, (**B**) 1) First peak vertical force, 2) Minimum vertical force, 3) Second peak vertical force, 4) Braking peak force, and 5) Propulsive peak force, and (**C**) 1) Vertical impulse, 2) Braking impulse, and 3) Propulsive impulse] between the lead limb and trail limb during obstacle crossing over 20 cm obstacle height condition (n=13), significant difference tested by paired *t*-test at *p*<0.05.

were found between the LL and TL in time to propulsive peak force (*p*=0.024), minimum vertical force (*p*=0.005), propulsive peak force (*p*=0.024), braking impulse (*p*=0.004), and propulsive impulse (*p*=0.010) (Figure 4). For crossing an obstacle 30 cm high, significant differences were found between LL and TL in first peak vertical force (*p*=0.001), minimum vertical force (*p*=0.001), braking peak force (*p*=0.010), propulsive peak force (*p*=0.002), braking impulse (*p*=0.001), and propulsive impulse (*p*=0.001) (Figure 5).

Comparisons of force variables among walking conditions in each of the LL and TL

Table 1 shows comparisons of the variables among walking conditions in the LL. Significant differences were found in time to minimum force [F (1.316, 15.795)=5.617, *p*=0.024], time to the second peak force [F (1.685, 20.217)=84.877, *p*<0.001], time to propulsive peak force [F (1.307, 15.683)=68.467, *p*<0.001], minimum vertical force [F (2.155, 25.857)=8.376, *p*=0.001], braking peak force [F (3, 36)=11.072, *p*<0.001], propulsive peak force [F (3, 36)=56.738, *p*<0.001], vertical impulse [F (1.135,

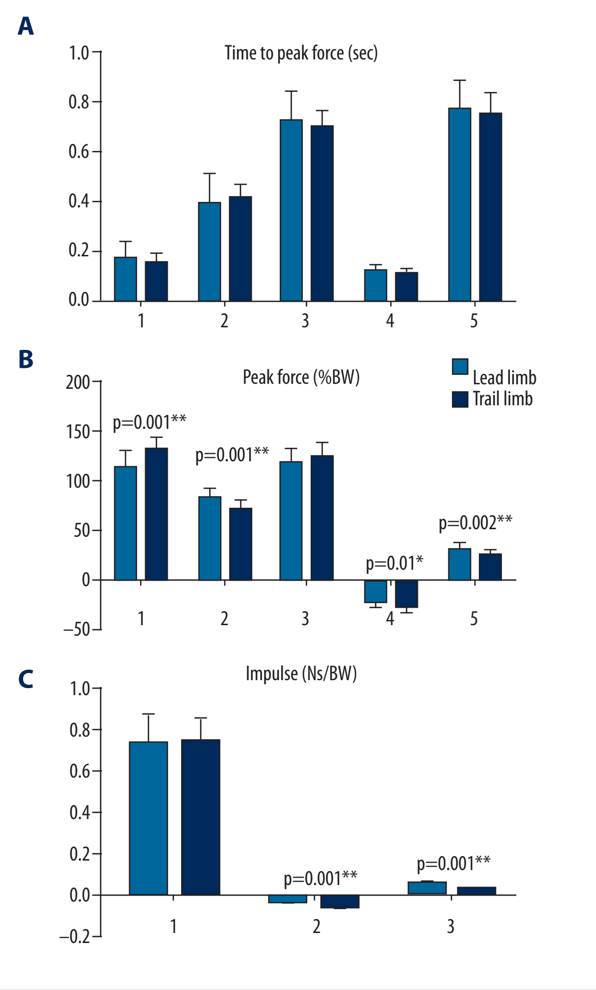

Figure 5. Comparisons of the variables [(**A**) 1) Time to the first peak force, 2) Time to minimum force, 3) Time to the second peak force, 4) Time to braking peak force, and 5) Time to propulsive peak force, (**B**) 1) First peak vertical force, 2) Minimum vertical force, 3) Second peak vertical force, 4) Braking peak force, and 5) Propulsive peak force, and (**C**) 1) Vertical impulse, 2) Braking impulse, and 3) Propulsive impulse] between the lead limb and trail limb during obstacle crossing over 30 cm obstacle height condition (n=13), significant difference tested by paired *t*-test at $p<0.05$.

13.615)=57.765, $p<0.001$], braking impulse [F (3, 36)=5.406, $p=0.004$], and propulsive impulse [F (1.319, 15.826)=73.276, $p<0.001$]. As the obstacle height increased, the LL had increased braking peak force, propulsive peak force, vertical impulse, braking impulse, and propulsive impulse.

Table 2 shows comparisons of the variables among walking conditions in the left or the TL. Significant differences were found in time to the first peak force [F (3, 36)=3.075, $p=0.040$], time to minimum force [F (3, 36)=23.248, $p<0.001$], time to the second peak force [F (1.804, 21.649)=84.877, $p<0.001$], time to propulsive peak force [F (3, 36)=81.209, $p<0.001$], first peak vertical force [F (1.694, 20.33)=26.53, $p<0.001$], minimum vertical force [F (3, 36)=7.194, $p=0.001$], second peak vertical force [F (3, 36)=3.315, $p=0.031$], braking peak force [F (1.362, 16.34)=19.607, $p<0.001$], propulsive peak force [F (3, 36)=5.159, $p=0.005$], vertical impulse [F (1.649, 19.788)=90.904, $p<0.001$], braking impulse [F (3, 36)=57.322, $p<0.001$], and propulsive impulse [F (3, 36)=33.814, $p<0.001$]. As the obstacle height increased, the TL had progressively greater values in the first peak vertical force, second peak vertical force, braking peak force, vertical impulse, braking impulse, and propulsive impulse. The minimum vertical force decreased as the obstacle height increased.

Discussion

We investigated kinetic and temporal strategies adopted in healthy young adults while stepping over obstacles of different heights. We determined the influence of condition and limb, as well as interaction effect of condition and limb, on kinetic variables while stepping over obstacles. In the no obstacle condition, similar patterns and values of the variables for the LL and TL were demonstrated as general gait character. The difference of force generation between the LL and TL increased with greater obstacle heights. Alterations of the temporal, force, and impulse were found in the vertical and anteroposterior directions.

We found changes in kinetic variables following different obstacle conditions. Stepping over a high obstacle required longer time to peak force, increased force, and increased impulse in both the LL and TL, except for time to braking peak force. The key moment of obstacle crossing happens when the LL lands after stepping over an obstacle and the TL must generate propulsive force to carry the body and the TL across the obstacle [10]; this is when the body weight is on the LL and the TL steps over the obstacle safely without visual feedback. Achievement of the task demonstrated postural and balance control on the TL, coupled with motor executive function of the LL.

Previous studies demonstrated that normal adults are able to adjust their limb to allow the foot to clear the obstacle. The lead foot clearance assessed by distance between toe and obstacle did not change even when the obstacle height was increased [4,15,21], whereas trail clearance increased with increasing obstacle height [21]. Control of human locomotion requires a proper motor coordination strategy that is safe and energy efficient. A high-stepping gait may be a strategy to avoid tripping over an obstacle [21]. Asymmetrical toe clearance can increase risk of tripping while elderly individuals try to step over an obstacle, with much lower distance of foot clearing of the TL than the LL [22]. However, a strategy of

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System]
[ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica]
[Chemical Abstracts/CAS] [Index Copernicus]

Table 1. Comparisons of the variables among conditions in the right limb or lead limb (n=13).

	Variables	No obstacle		Height 5-cm		Height 20-cm		Height 30-cm		df	F	p-value*	Partial Eta Squared	Least significant difference (LSD)					
		Right limb		Lead limb		Lead limb		Lead limb						p-value[1]	p-value[2]	p-value[3]	p-value[4]	p-value[5]	p-value[6]
		Mean	SD	Mean	SD	Mean	SD	Mean	SD										
1	Time to the first peak force (s)	0.15	0.03	0.15	0.04	0.17	0.07	0.15	0.07	3	0.636$^{\#}$	0.597	0.050	NS	NS	NS	NS	NS	NS
2	Time to minimum force (s)	0.29	0.04	0.32	0.05	0.35	0.07	0.39	0.12	1.316	5.617^{+}	**0.024**	0.319	**0.023**	**0.006**	**0.006**	**0.012**	**0.044**	NS
3	Time to the second peak force (s)	0.46	0.05	0.52	0.06	0.62	0.09	0.72	0.12	1.685	84.877^{+}	**<0.001**	0.876	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
4	Time to braking peak force (s)	0.10	0.02	0.10	0.03	0.10	0.02	0.12	0.02	3	2.868$^{\#}$	0.05	0.193	NS	NS	NS	NS	NS	NS
5	Time to propulsive peak force (s)	0.54	0.06	0.58	0.07	0.66	0.10	0.77	0.12	1.307	68.467^{+}	**<0.001**	**0.851**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
6	First peak vertical force (%BW)	111.55	8.47	119.29	12.75	119.56	20.98	114.92	15.26	1.93	2.183^{+}	0.137	0.154	NS	NS	NS	NS	NS	NS
7	Minimum vertical force (%BW)	81.68	9.09	77.59	9.92	80.17	10.46	84.29	9.48	2.155	8.376^{+}	**0.001**	0.411	**<0.001**	NS	NS	NS	**<0.001**	**0.015**
8	Second peak vertical force (%BW)	117.87	8.39	120.50	8.89	120.34	13.20	120.61	12.79	3	0.794$^{\#}$	0.505	0.062	NS	NS	NS	NS	NS	NS
9	Braking peak force (%BW)	−17.17	2.19	−22.28	4.71	−23.21	6.12	−21.94	5.73	3	11.072$^{\#}$	**<0.001**	0.480	**<0.001**	**<0.001**	**0.001**	NS	NS	NS
10	Propulsive peak force (%BW)	23.94	3.32	26.75	3.71	30.62	3.76	33.27	5.42	3	56.738$^{\#}$	**<0.001**	0.825	**0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.01**
11	Vertical impulse (Ns/BW)	0.53	0.07	0.57	0.08	0.65	0.11	0.74	0.14	1.135	57.765^{+}	**<0.001**	0.828	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
12	Braking impulse (Ns/BW)	−0.027	0.004	−0.032	0.007	−0.032	0.007	−0.030	0.008	3	5.406$^{\#}$	**0.004**	0.311	**<0.001**	**0.001**	NS	NS	NS	NS
13	Propulsive impulse (Ns/BW)	0.032	0.005	0.038	0.007	0.049	0.009	0.063	0.014	1.319	73.276^{+}	**<0.001**	0.859	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

* Significant difference tested among conditions by one way repeated measures ANOVA; NS – not significant; $^{\#}$ sphericity assumed; $^{+}$ Greenhouse-Geisser pair of difference tested by LSD between; [1] no obstacle and 5 cm height obstacle crossing conditions; [2] no obstacle and 20 cm height obstacle crossing conditions; [3] no obstacle and 30 cm height obstacle crossing conditions; [4] 5 cm and 20 cm height obstacle crossing conditions; [5] 5 cm and 30 cm height obstacle crossing conditions; [6] 20 cm and 30 cm height obstacle crossing conditions.

Table 2. Comparisons of the variables among conditions in the left limb or trail limb (n=13).

	Variables	No obstacle		Height 5-cm		Height 20-cm		Height 30-cm		df	F	p-value*	Partial Eta Squared	Least significant difference (LSD)					
		Right limb		Lead limb		Lead limb		Lead limb						p-value[1]	p-value[2]	p-value[3]	p-value[4]	p-value[5]	p-value[6]
		Mean	SD	Mean	SD	Mean	SD	Mean	SD										
1	Time to the first peak force (s)	0.15	0.03	0.16	0.03	0.15	0.03	0.14	0.03	3	3.075[#]	**0.040**	0.204	NS	NS	NS	NS	**0.020**	NS
2	Time to minimum force (s)	0.29	0.04	0.32	0.06	0.36	0.08	0.41	0.06	3	23.248[#]	**<0.001**	0.660	**0.018**	**<0.001**	**<0.001**	**0.008**	**<0.001**	**0.024**
3	Time to the second peak force (s)	0.47	0.05	0.54	0.07	0.61	0.12	0.70	0.07	1.804	51.931[+]	**<0.001**	0.812	**<0.001**	**<0.001**	**<0.001**	**0.003**	**<0.001**	**0.006**
4	Time to braking peak force (s)	0.11	0.02	0.11	0.02	0.11	0.01	0.11	0.02	3	0.858[#]	0.472	0.067	NS	NS	NS	NS	NS	NS
5	Time to propulsive peak force (s)	0.55	0.06	0.60	0.08	0.69	0.10	0.75	0.09	3	81.209[#]	**<0.001**	0.871	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
6	First peak vertical force (%BW)	109.81	8.81	118.64	9.20	128.41	9.58	132.20	12.83	1.694	26.53[+]	<0.001	**0.689**	**0.001**	**<0.001**	**<0.001**	**<0.001**	**0.004**	NS
7	Minimum vertical force (%BW)	79.23	7.27	76.37	8.16	73.96	7.92	71.73	9.64	3	7.194[#]	**0.001**	0.375	NS	**0.005**	**0.002**	NS	**0.016**	NS
8	Second peak vertical force (%BW)	118.11	10.57	118.28	13.81	118.82	15.92	125.85	13.36	3	3.315[#]	**0.031**	0.216	NS	NS	**0.043**	NS	**0.021**	NS
9	Braking peak force (%BW)	-17.44	4.72	-20.40	4.91	-24.16	4.58	-26.78	6.47	1.362	19.607[+]	**<0.001**	0.620	**<0.001**	**<0.001**	**<0.001**	**0.001**	**0.005**	NS
10	Propulsive peak force (%BW)	23.57	2.92	26.85	4.20	27.71	4.08	25.72	4.37	3	5.159[#]	**0.005**	0.301	**0.014**	**0.002**	NS	NS	NS	NS
11	Vertical impulse (Ns/BW)	0.520	0.074	0.583	0.091	0.676	0.129	0.750	0.112	1.649	90.904[+]	**<0.001**	0.883	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
12	Braking impulse (Ns/BW)	-0.027	0.007	-0.034	0.011	-0.044	0.011	-0.056	0.009	3	57.322[#]	**<0.001**	0.827	**0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.001**
13	Propulsive impulse (Ns/BW)	0.032	0.005	0.038	0.006	0.042	0.006	0.042	0.004	3	33.814[#]	**<0.001**	0.738	**0.001**	**<0.001**	**<0.001**	**0.001**	**0.019**	NS

* Significant difference tested among conditions by one way repeated measures ANOVA; NS – not significant; [#] sphericity assumed; [+] Greenhouse-Geisser pair of difference tested by LSD between; [1] no obstacle and 5 cm height obstacle crossing conditions; [2] no obstacle and 20 cm height obstacle crossing conditions; [3] no obstacle and 30 cm height obstacle crossing conditions; [4] 5 cm and 20 cm height obstacle crossing conditions; [5] 5 cm and 30 cm height obstacle crossing conditions; [6] 20 cm and 30 cm height obstacle crossing conditions.

high stepping or excessive asymmetrical gait modulation creates high demand of metabolic energy and reduces control for normal movement. Previous research on gait pattern adaptations when stepping over obstacles of different heights demonstrated that step length [21] was not influenced by the height, but that crossing speed decreased [23] and step duration increased [23] across obstacle heights. Over different obstacle heights, the center of pressure velocity during the loading response phase was not changed, but decreased during midstance [24]. In the present study, we found kinetic alteration while stepping over obstacles of different heights, as demonstrated by adaptability of obstacle crossing in young healthy adults. The time to minimum force, time to the second peak force, and time to propulsive peak force were increased following the increased obstacle height, both in the LL and TL. Increase in braking and propulsive peak forces and increase in vertical and propulsive impulses were demonstrated when height was increased, both in the LL and TL. Moreover, the TL had greater adaptability in force variables compared to the LL. These findings demonstrated an increase in the first peak vertical force and braking impulse and a decrease in minimum force when height was increased only in the TL. The findings are consistent with a previous kinetic study [10], in which Begg et al. [10] reported that the TL generated greater vertical and propulsive forces during the push-off phase than the LL.

Obstacle crossing is requires mutually interdependent control of the LL and TL. For normal control, we found that the difference between LL and TL was increased in the tested variables when the height of obstacle was increased. Comparisons among conditions in each limb demonstrated the adaptability of time and force control when the height was increased. Time to minimum force, time to the second peak force, and time to braking peak force were delayed when height was increased. Braking peak force was increased with increased obstacle height, but was relatively constant when changing from the 20-cm to 30-cm obstacle height in both the LL and TL. When confronted with obstacles of different heights, body movement is modified, allowing proper force generation and absorption, perhaps associated with maintaining postural balance and reducing energy consumption. This is supported by the unchanged values of some variables such as braking impulse of the LL and propulsive impulse of the TL when obstacle height changed from 20 cm to 30 cm. It is also important to note that the force–time characteristic under the LL reflects not only control of TL over obstacles but also landing of the LL after clearing obstacles.

Conclusions

Our results show that the constraints of stepping over obstacles imposed different kinetic demands on the LL and TL, with the complicated interaction of force time characteristics. Strategic movement control during obstacle crossing with different heights in young healthy subjects indicated the ability to adapt movement to environmental conditions. These findings may be used as a model when comparing healthy young people to the elderly and to those who have physical impairments. Further research should investigate the intersegmental dynamic control and muscle activity underlying locomotor adjustments during obstacle crossing.

Acknowledgements

The authors wish to thank Ms. Nithipak Thammayon, Ms. Narinrat Somwhong, and Ms. Rawipa Kongsilp for their assistances in data collection. In addition, we appreciate all the support we received from members of the Faculty of Physical Therapy, Mahidol University.

Statements and declarations regarding conflicts of interest

There were no direct or indirect relationships such as equity, consulting, research support and funding, or corporate patents dealing with the material or subject matter of this contribution.

References:

1. Pavol MJ, Owings TM, Foley KT, Grabiner MD: Mechanisms leading to a fall from an induced trip in healthy older adults. J Gerontol A Biol Sci Med Sci, 2001; 56: M428–37
2. Pavol MJ, Owings TM, Foley KT, Grabiner MD: Gait characteristics as risk factors for falling from trips induced in older adults. J Gerontol A Biol Sci Med Sci, 1999; 54: M583–90
3. Novak AC, Deshpande N: Effects of aging on whole body and segmental control while obstacle crossing under impaired sensory conditions. Hum Mov Sci, 2014; 35: 121–30
4. Chen HL, Lu TW, Wang TM, Huang SC: Biomechanical strategies for successful obstacle crossing with the trailing limb in older adults with medial compartment knee osteoarthritis. J Biomech, 2008; 41: 753–61
5. Galna B, Murphy AT, Morris ME: Obstacle crossing in people with Parkinson's disease: foot clearance and spatiotemporal deficits. Hum Mov Sci, 2010; 29: 843–52
6. Galna B, Peters A, Murphy AT, Morris ME: Obstacle crossing deficits in older adults: a systematic review. Gait Posture, 2009; 30: 270–75
7. Liao YY, Yang YR, Wu YR, Wang RY: Factors influencing obstacle crossing performance in patients with Parkinson's disease. PLoS One, 2014; 13: e84245
8. Lu TW, Chen HL, Wang TM: Obstacle crossing in older adults with medial compartment knee osteoarthritis. Gait Posture, 2007; 26: 553–59
9. Said CM, Goldie PA, Patla AE, Sparrow WA: Effect of stroke on step characteristics of obstacle crossing. Arch Phys Med Rehabil, 2001; 82: 1712–19
10. Begg RK, Sparrow WA, Lythgo ND: Time-domain analysis of foot-ground reaction forces in negotiating obstacles. Gait Posture, 1998; 7: 99–109
11. Huang SC, Lu TW, Chen HL et al: Age and height effects on the center of mass and center of pressure inclination angles during obstacle-crossing. Med Eng Phys, 2008; 30: 968–75

12. Bovonsunthonchai S, Hiengkaew V, Vachalathiti R: Obstacle crossing characteristics in the healthy young female and elderly female subjects. Siriraj Med J, 2012; 64: 52–56
13. Timmis MA, Buckley JG: Obstacle crossing during locomotion: visual exproprioceptive information is used in an online mode to update foot placement before the obstacle but not swing trajectory over it. Gait Posture, 2012; 36: 160–62
14. Rietdyk S, Rhea CK: The effect of the visual characteristics of obstacles on risk of tripping and gait parameters during locomotion. Ophthalmic Physiol Opt, 2011; 31: 302–10
15. Lu TW, Chen HL, Chen SC: Comparisons of the lower limb kinematics between young and older adults when crossing obstacles of different heights. Gait Posture, 2006; 23: 471–79
16. McFadyen BJ, Prince F: Avoidance and accommodation of surface height changes by healthy, community-dwelling, young, and elderly men. J Gerontol A Biol Sci Med Sci, 2002; 57: B166–74
17. Chou LS, Draganich LF: Stepping over an obstacle increases the motions and moments of the joints of the trailing limb in young adults. J Biomech, 1997; 30: 331–37
18. Wang TY, Bhatt T, Yang F, Pai YC: Adaptive control reduces trip-induced forward gait instability among young adults. J Biomech, 2012; 45: 1169–75
19. Gorwa J, Dworak LB, Michnik R, Jurkojc J: Kinematic analysis of modern dance movement “stag jump” within the context of impact loads, injury to the locomotor system and its prevention. Med Sci Monit, 2014; 20: 1082–89
20. Ericksen HM, Gribble PA, Pfile KR, Pietrosimone BG: Different modes of feedback and peak vertical ground reaction force during jump landing: a systematic review. J Athl Train, 2013; 48: 685–95
21. Sparrow WA, Shinkfield A, Chow S, Begg RK: Characteristics of gait in stepping over obstacles. Hum Mov Sci, 1996; 15: 605–22
22. Di Fabio RP, Kurszewski WM, Jorgenson EE, Kunz RC: Footlift asymmetry during obstacle avoidance in high-risk elderly. J Am Geriatr Soc, 2004; 52: 2088–93
23. Chen HC, Ashton-Miller JA, Alexander MD, Schultz AB: Stepping over obstacles. Gait patterns of healthy young and old adults. J Gerontol, 1991; 46: 196–203
24. Wang Y, Watanabe K: The relationship between obstacle height and center of pressure velocity during obstacle crossing. Gait Posture, 2008; 27: 172–75