The effect of obstacle height and maximum step length (MSL) on obstacle crossing in healthy adults

Sang-Joon Park[1], Yohei Otaka[2], Shinpei Okada[1], Hiroharu Kamioka[3], Hiroyasu Okuizumi[4], Taiki Komatu[5] and Yoshiteru Mutoh[6]

[1] *Physical Education and Medicine Research Foundation, 6-1 Nunoshita, Tomi, Nagano 389-0402, Japan*

[2] *Tokyo bay Rehabilitation Hospital, 4-1-1 Narashino Yathu, Chiba 275-0026, Japan*

[3] *Faculty of Regional Environment Science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku, Tokyo 156-8502, Japan*

[4] *Tomi City Hot Spring Clinic, 6-1 Nunoshita, Tomi, Nagano 389-0402, Japan*

[5] *School of Health Science Department of Physical Therapy Tokyo University of Technology, 5-23-22 Nishikamata, Ohta-ku, Tokyo 144-8635, Japan*

[6] *Todai Policy Alternatives Research Institute, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*

Abstract　　In this study, we investigated whether subjects with a Lower Maximum Step Length (MSL) Percentage (LMP) display unstable locomotion while negotiating an obstacle. Data were collected using a three-dimensional motion analysis system. The toe-obstacle clearance of the leading limb was monitored in 10 young adults while stepping over three height obstacles from 30%, 40% and 50% of MSL. The vertical clearance at the time of the obstacle crossing decreased systematically with more complicated experimental set up. In particular, subjects with LMP showed smaller clearances than subjects with a Higher Maximum step length Percentage (HMP). Furthermore, a significant correlation was observed between the toe-obstacle clearance and MSL. The mean of variance value of toe-obstacle clearance of the leading limb differed between the subjects with LMP and those with HMP. Our findings help to explain the relation of MSL and gait adaption ability to negotiate obstacles safely during obstacles crossing.

Jpn J Phys Fitness Sports Med, 61(1): 103-109 (2012)

Keywords : obstacle height, obstacle distance, maximum step length (MSL), toe-obstacle clearance, mean of variance value of toe-obstacle clearance

Introduction

During daily activities, people have to accommodate changes in support surface elevation, and this adaptability is required continuously to modify behavior in response to new situations during gait[1-3]. For this reason, gait adaptation during locomotion is considered an important factor to modulate the body safely and efficiently across the ground level and surface elevations. If the adaptation ability is impaired, various problems (e.g. falls and fall-related injuries) may occur during locomotion to negotiate a raised surface. In fact, not a few studies have reported that a large proportion of falls in public places occur on steps and during the crossing of obstacles[4-7]. Over the past few decades, many studies have been conducted to clarify characteristics of gait adaptation in stair walking and stepping over an obstacle during locomotion. For example, they have examined the movement patterns and joint moments of the stance limb and the trailing limb[8,9], gait patterns[10,11] and the motion of the body's center of mass (COM)[12,13] during obstacle crossing. The results of

these studies have demonstrated that the measurement of sway patterns of COM could be used as an indicator of the whole body balance when walking on different surfaces. Furthermore, others have examined clearance behavior during locomotion in negotiating a raised surface and in stepping on a stair[14-17]. These studies have revealed that the presence of the obstacle during locomotion increases the ground clearance by flexing the swing limb more than the normal locomotion. According to the varied laboratory studies mentioned above, many researchers have concluded that the take-off clearance of lead toe and landing distance are important parameters to estimate how closely the swing limb approaches the obstacle when stepping over, and that this information is useful to understand how the lower limb trajectory is controlled in traversing an obstacle[8,10,12,16]. However, no study has provided data showing gradual changes of the obstacle clearance when stepping over an obstacle in a multiple situation (changing obstacle height and distance from start position). Most previous studies to clarify the vertical obstacle clearance during obstacle crossing have utilized a simple task, such

as a four obstacles height task or an unchanging starting position from an obstacle[8-10,12,13,16,18]. Those studies did not obtain more complete information to clarify the gradual changes of the vertical obstacle clearance when stepping over an obstacle. Our current study is to examine multiple factors that may affect obstacle clearance pattern related to gait adaptability. For this measurement, we set diverse starting positions and obstacle heights using Maximum Step Length (MSL) and the lower limb length data. This experimental design considered MSL characteristic may not only reveal gradual pattern changes of the obstacle clearance in a complication situation, but also the effects of MSL and obstacle height when stepping over an obstacle in healthy adults.

In this study, we examined the vertical obstacle clearance (toe-obstacle clearance) of the leading toe and the mean of variance value of toe-obstacle clearance between trials in each task, respectively. Our hypothesis is that subjects with a Lower MSL Percentage (LMP) display smaller vertical clearance of the leading toe and larger variance value of toe-obstacle clearance of the leading limb during obstacle crossing than subjects with a Higher MSL Percentage (HMP).

Methods

Participants   Volunteers were recruited from the community willing to participate in our experiments. The detailed medical history was solicited from all subjects. All subjects were excluded from the study if they had any history of neurological or orthopedic conditions likely to affect their balance during mobility. As a results, 10 healthy volunteers ranging in age from 21-28 years (age, 24.3±2.5yr, BMI, 23±3.6kg/m², Height, 167.3±7.4cm, Weight, 65±14.3kg, Lower limb length, 86.3±12.7cm, MSL test, 92.8±16.8cm) were recruited. The Human Studies Ethics Committee at the Hospital of KEIYU in Japan approved of this study. The purpose and methods of the study were explained to all the subjects, and informed consent was obtained prior to the experiments.

All subjects were given a Maximum Step Length (MSL) test. Each subject was tested for MSL in the front direction. The subjects were instructed to step maximally forward direction with preferred limb then to align the trailing limb near to the position of the leading limb. MSL was calculated for one leg distance (from the toe of the trailing limb to the heel of the leading foot) as the average maximum step length of 10 trials. Moreover, the LMP (Lower MSL Percentage) and HMP (Higher MSL Percentage) were calculated by the percentage from the lower limb length. Firstly, a HMP was defined when the average of MSL test of 10 trials exceeded the individual's lower limb length. However, if the average of MSL did not exceed the individual's lower limb length, it was defined as a LMP. The lower limb length was measured from the greater trochanter to the plantar surface of the foot (see Fig 1).
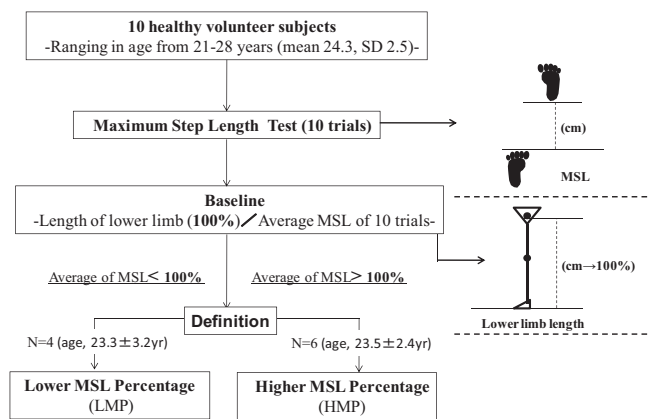

Fig 1.   Testing protocols to define lower MSL percentage (LMP) and higher MSL percentage (HMP).

The LMP was comprised of four subjects (age, 23.3±3.2yr, p=0.9, BMI, 20.5±1.8kg/m², p=0.1, Height, 172.3±2.5cm, p=0.05, Weight, 61±5.2kg, p=0.9, Lower limb length, 89.3±2.3cm, p=0.08), and the HMP was comprised of six subjects (age, 23.5±2.4yr, BMI, 22.8±1.5kg/m², Height, 163.3±6.8cm, Weight, 61.3±8.4kg, Lower limb length, 84.3±4.8cm).

Experimental Procedures   The subjects were asked to stand in barefoot on force plate, and to step over an obstacle at a comfortable speed with the right limb or the left limb (the preferred limb). Two force plates were used in order to provide stable experiment condition. In terms of comfortable speed, a lot of previous studies have mentioned that it is better idea to control the speed for data comparison. In our experiment, however, subjects were only instructed to step over the obstacle at a comfortable speed because we have performed a more complicated experimental set up than normal walking to identify gradual changes of the obstacle clearance pattern focused on gait adaptability. In fact, not a few previous studies to evaluate the characteristics of clearance when stepping over an obstacle have mainly examined sway pattern, moments of joints and toe-obstacle distance with a comfortable self-selected speed[12,16,18]. As protocol of measurement, the subjects stood in a predetermined position (Distance of 30, 40, and 50% of MSL from an obstacle, respectively) then stepped over an obstacle placed at the base-line location, and continued walking. This task was repeated at the starting position of 30, 40, and 50% of MSL from an obstacle, and repeated for three obstacle heights (15, 25, and 35% of the subject's lower limb length). Subjects were instructed to step over the obstacle without contacting the obstacle or losing balance. Ten trials were collected for each task (for each height at each distance) and 90 successful trails were recorded for each subject.

The three-dimensional motion analysis system (Kinema Tracer: made by KISSEI Comtec, Inc, Japan.) was used in this study. A four-camera system was used to collect 3-D marker trajectory data at a sampling rate of 60Hz, and the

kinematic raw data were smoothed with a low-pass digital filter with a cutoff frequency of 8Hz. The video cameras were positioned approximately 3m from the platform edges. The obstacle consisted of a black elastic band (8 mm wide and 2 mm thick). Eight 2.5 cm light reflective markers identified various landmarks on the subject and the obstacle. Reflective markers were attached to the big toe (between the 2nd and 3rd metatarsal heads), the ankle and the knee of the subjects' left and right limbs. The subjects also wore a safety harness with chest and seat components that was attached to a trolley system secured to a concrete ceiling in order to protect the subjects from any accidental falls. A diagrammatic representation of a subject undertaking the test is shown in Fig 2.

Data analysis   The 3-D marker trajectory data were obtained from each trial for each subject. The toe-obstacle clearance was calculated as the vertical distance between the toe marker and the obstacle point marker at the instant when the toe marker was directly above the obstacle. The mean of variance value of toe-obstacle clearance was calculated as variance values of the vertical toe elevation between each trial, respectively. Also the vertical toe elevation was defined as the vertical distance from the point marker of obstacle to the toe-marker of lead (swing) foot at the instant when the toe marker was directly above the obstacle. The kinematic data were analyzed during the period beginning with the lead heel off before stepping over the obstacle to the heel-strike of the lead limb after crossing the obstacle (see Fig 2). Independent variables of the study were subject group (HMP and LMP), the obstacles heights and the distance form obstacle. Effects of subject group, the obstacles heights condition (15, 25, and 35% of the subject's lower limb length) and the predetermined starting positions (Distance of 30, 40, and 50% of

MSL from an obstacle) on the dependent variables were carried using two-way repeated-measures analysis of variance. The dependent variables consisted of the toe-obstacle clearance of the leading limb and the mean of variance value of toe-obstacle clearance of the leading limb in each task. In addition, Pearson correlation analysis was performed to assess the strength of the associations between the MSL and the toe-obstacle clearance of the leading limb when stepping over each height obstacle. All statistical analyses were performed using SPSS 17.0J for Windows (SPSS Inc, Japan, Tokyo). For all analyses, statistical significance levels were set at $p < 0.05$.

Results

Effect of MSL and obstacle height condition   The y-z trajectories of the three markers, the knee, the ankle and the toe, for one subject during the swing period beginning with the lead heel off just before crossing the obstacle to the lead heel contact just after crossing the obstacle are averaged over ten trials per task, and representative statokinesigrams depicting the profiles for the different obstacle heights and starting positions by MSL percentage were constructed. In general, low clearances may demand a very precise foot trajectory control, and a relatively higher clearance may reflect a safe margin while stepping over the obstacle. And inappropriate approaching of the leading limb at the first movement stage to negotiate the obstacle is as a cause of unstable trajectory of the leading limb. Fig 3 shows a sample graph describing the change in the trajectory of various markers as the subject crossed obstacles in each task.

No incidents of falling and fall-related occurred for any of the obstacle height conditions and distance of obstacle conditions in either group. The results of toe-obstacle clearance and variance value of toe-obstacle clearance in
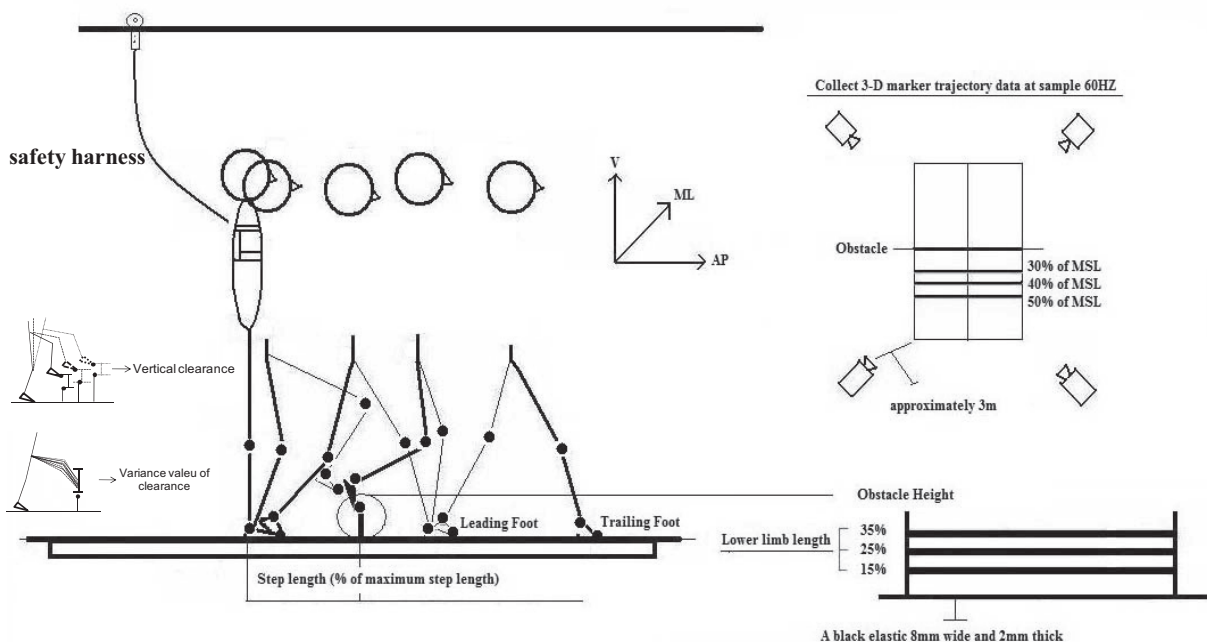

Fig 2.   Experimental set up illustrating the starting position and each obstacle height when stepping over the obstacle.
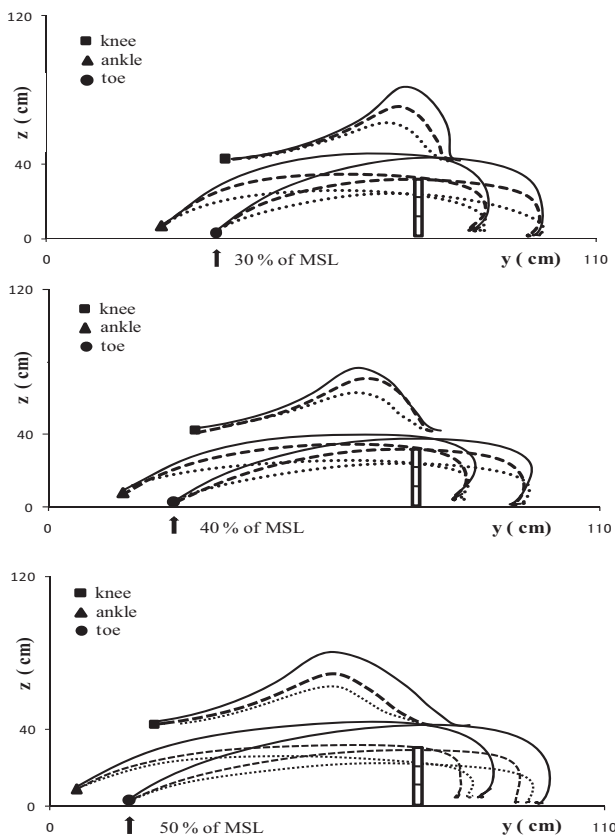
Fig 3.　The average of ten trial precondition in y-z trajectories of three markers placed on the leading limbs: 15% height obstacle of lower limb length (····), 25% height obstacle of lower limb length (− −), 35% height obstacle of lower limb length (——) are shown from the starting position in 30%, 40% and 50% of step maximally (maximum step length or MSL) to crossing the obstacle (sample graph).

the each obstacle height between HMP and LMP group are summarized in Table 1. There were a significant difference between HMP group and LMP group for toe-obstacle clearance parameter in the 15, 25, and 35% obstacle height with 30% starting position ($p < 0.05$) and 15, 25, and 35% obstacle height with 40%, 50% starting position ($p < 0.01$, $p < 0.001$, respectively). The toe-obstacle clearance decreased linearly as the obstacle height increased in 40%, 50% starting position in two groups ($p < 0.05$, $p < 0.01$, respectively). Moreover, we have calculated obstacle clearance between the toe marker and the obstacle point marker at the instant when the toe marker was directly above the obstacle in each task, respectively, and estimated variance value of toe-obstacle clearance among trials of all tasks of subjects. As a result, The mean of variance value of toe-obstacle clearance over the obstacle between two groups showed significance in the 15, 25, and 35% obstacle height with 50% starting position ($p < 0.05$). Also, The mean of variance value of toe-obstacle clearance over the obstacle increased linearly as the obstacle height increased in 50% starting position ($p < 0.05$).

The results of toe-obstacle clearance and variance value of toe-obstacle clearance in the each distance from

obstacle between HMP and LMP group are presented in Table 2. There were no significant differences between subject groups for any of two dependent parameters, the effect of distance from obstacle too, in 30, 40, and 50% starting position from obstacle with 15% obstacle height. However, there were significant starting positions×subject groups interaction effect for the toe-obstacle clearance in the 30, 40, and 50% starting position with the 25%, 35% obstacle height ($p < 0.05$, $p < 0.01$, respectively). The toe-obstacle clearance during the step over an obstacle was affected by MSL capability and distance from obstacle, decreasing linearly as tasks of the obstacle height and the starting position became more difficult. Furthermore, The mean of variance value of toe-obstacle clearance in the 30, 40, and 50% starting position with the 35% obstacle height showed starting positions×subject groups interaction effect ($p < 0.05$). The mean of variance value of toe-obstacle clearance when stepping over an obstacle was also affected by MSL capability and distance from obstacle, increasing linearly with a complication situation.

Typically, the vertical clearance at the time of obstacle crossing decreased with the increase in the obstacle height and the starting position, and all subjects displayed a similar change pattern of toe-obstacle clearance with changing obstacle heights and starting positions while crossing the obstacle. Interestingly, the vertical clearance of LMP subjects decreased linearly as the obstacle height and distance from obstacle increased than that of HMP subjects. All subjects showed a smaller toe-obstacle clearance during stepping over the 35% obstacle height from each starting position compared with the 15% obstacle height and the 25% obstacle height (Table 1, 2). Also, The mean of variance value of toe-obstacle clearance in subjects with LMP subjects showed larger from the 40% starting position (35% obstacle height) and the 50% starting position (25%, 35% obstacle height).

In addition, the toe-obstacle clearance of the leading limb when stepping over the obstacle showed a significant correlation with MSL. The relationship between the toe-obstacle clearance and MSL showed a significant correlation in the 50% starting position (25% obstacle height: $r = 0.837$, $p < 0.05$) and in the 30, 40, and 50% starting position (35% obstacle height: 30%, $r = 0.794$, $p < 0.05$, 40%, $r = 0.844$, $p < 0.01$, 50%, $r = 0.836$, $p < 0.01$). However, there is no significant correlation in the 30, 40, and 50% starting position (15% obstacle heights: 30%, $r = 0.274$, $p = 0.76$, 40%, $r = 0.240$, $p = 0.91$, 50%, $r = 0.352$, $p = 0.36$) and in the 30%, 40% starting position (25% obstacle heights: 30%, $r = 0.836$, $p = 0.07$, 40%, $r = 0.620$, $p = 0.14$) (see Fig 4).

Discussion

The primary focus of this study was to examine the gradual changes of the toe-obstacle clearance of the leading limb in a varied experimental set up to test the hypothesis that LMP subjects display smaller toe-obstacle

Table 1. Comparison of toe-obstacle clearance and variance value of toe-obstacle clearance in the each obstacle height between HMP and LMP group.


→ Vertical clearance
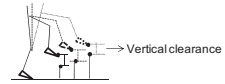
Obstacle height (%)	15%		25%		35%		p -value[a]	
stage 1 (Distance of 30% of MSL from an obstacle,)	LMP	HMP	LMP	HMP	LMP	HMP	† p_h=0.071	‡ p_h=0.84
toe-obstacle clearance (cm) †	11.3(±0.6)[b]	11.9(±0.9)	9.6(±0.3)	11.2(±0.9)	6.1(±0.4)	10.6(±0.6)	p_g<0.05	p_g=0.77
variance value of toe-obstacle clearance (mean) ‡	1.2(±0.1)	1.3(±0.3)	1.1(±0.1)	1.1(±0.1)	1.6(±0.3)	1.6(±0.2)	p_{hg}=0.21	p_{hg}=0.47
stage 2 (Distance of 40% of MSL from an obstacle)							p_h<0.05	p_h=0.068
toe-obstacle clearance (cm)	10.2(±0.6)	11.5(±0.6)	9.1(±0.3)	9.9(±1.5)	3.8(±1.6)	9.1(±1.2)	p_g<0.01	p_g=0.061
variance value of toe-obstacle clearance (mean)	2.7(±0.4)	1.9(±0.3)	2.1(±0.1)	1.9(±0.1)	3(±0.2)	2.7(±0.5)	p_{hg}=0.097	p_{hg}=0.24
stage 3 (Distance of 50% of MSL from an obstacle)							p_h<0.01	p_h<0.05
toe-obstacle clearance (cm)	9(±0.6)	7.8(±0.2)	5.4(±1)	7.5(±0.2)	2.8(±1.4)	6.8(±0.5)	p_g<0.001	p_g<0.05
variance value of toe-obstacle clearance (mean)	2.3(±0.2)	2.3(±0.3)	3.6(±0.4)	2.4(±0.4)	4.3(±0.4)	2.7(±0.3)	p_{hg}=0.063	p_{hg}=0.47

[a] p_h, p -value for the effect of obstacle height; p_g, p -value for the effect of group, p_{hg}, p -value for the interaction between obstacle height and group
[b] Mean value, with standard deviation in parentheses.

Table 2. Comparison of toe-obstacle clearance and variance value of toe-obstacle clearance in the each distance from obstacle between HMP and LMP group.

→ Variance valeu of clearance
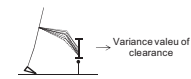
Diatance from obstacle (%)	30%		40%		50%		p -value[a]	
stage 1 (Obstacle heights of 15% of the lower limb length)	LMP	HMP	LMP	HMP	LMP	HMP	† p_d=0.068	‡ p_d=0.082
toe-obstacle clearance (cm) †	11.3(±0.6)[b]	11.9(±0.9)	10.2(±0.6)	11.5(±0.6)	9(±0.6)	7.8(±0.2)	p_g=0.057	p_g=0.33
variance value of toe-obstacle clearance (mean) ‡	1.2(±0.1)	1.3(±0.3)	2.7(±0.4)	1.9(±0.3)	2.3(±0.2)	2.3(±0.3)	p_{dg}=0.343	p_{dg}=0.495
stage 2 (Obstacle heights of 25% of the lower limb length)							p_d<0.05	p_d=0.059
toe-obstacle clearance (cm)	9.6(±0.3)	11.2(±0.9)	9.1(±0.3)	9.9(±1.5)	5.4(±1)	7.5(±0.2)	p_g<0.05	p_g=0.053
variance value of toe-obstacle clearance (mean)	1.1(±0.1)	1.1(±0.1)	2.1(±0.1)	1.9(±0.1)	3.6(±0.4)	2.4(±0.4)	p_{dg}<0.05	p_{dg}=0.221
stage 3 (Obstacle heights of 35% of the lower limb length)							p_d<0.001	p_d<0.05
toe-obstacle clearance (cm)	6.1(±0.4)	10.6(±0.6)	3.8(±1.6)	9.1(±1.2)	2.8(±1.4)	6.8(±0.5)	p_g<0.001	p_g<0.05
variance value of toe-obstacle clearance (mean)	1.6(±0.3)	1.6(±0.2)	3(±0.2)	2.7(±0.5)	4.3(±0.4)	2.7(±0.3)	p_{dg}<0.01	p_{dg}<0.05

[a] p_d, p -value for the effect of distance from obstacle; p_g, p -value for the effect of group, p_{dg}, p -value for the interaction between diatance from obstacle and group
[b] Mean value, with standard deviation in parentheses.

clearance margins of the leading limb and exhibit a larger variance value of toe-obstacle clearance in the leading limb than HMP subjects.

In this study, the change pattern of the obstacle clearance showed a significant difference between HMP group and LMP group. Subject groups successfully negotiated each obstacle height from each starting position with a safe margin of leading toe clearance, whereas the LMP subjects exhibited a significantly smaller vertical toe-obstacle clearance compared to the HMP subjects (Table 1, 2). When the swing toe was above the obstacle in each starting position, the vertical clearance of all subjects decreased systematically. In particular, the LMP subjects demonstrated a smaller vertical clearance compared to the HMP subjects. Besides, the relationship between the toe-obstacle clearance of the leading limb and MSL showed a linear correlation as tasks became more complicated. The most interesting phenomenon observed was that in approaching from the far starting position to the 25%, 35% obstacle height, the LMP subjects demonstrated restricted toe-obstacle clearances (Table 1). Generally, such low clearances may demand a very precise foot trajectory control while crossing the obstacle, and a relatively higher clearance may reflect a safe margin while stepping over the obstacle[1]. In our experiment, LMP subjects safely modulated the vertical toe clearance at the first movement stage to negotiate the obstacle, but the vertical toe clearance of the leading limb while stepping over

the obstacle demonstrated restricted toe-obstacle clearances, and it seems as a cause of unstable trajectory. This phenomenon has connection with a cause to make narrow toe clearance margin while stepping over obstacle. At the same time, it is also not irrelevant to make a significantly larger variance value of toe-obstacle clearance between HMP and LMP group (Table 1, 2). To our knowledge, gait adaptability to negotiate obstacles safely is dependent on a stable foot trajectory control, muscular strength and neuro-muscular function[1,14,16]. When we consider these previous studies mentioned above, we can be interpreted that small vertical distance of the leading toe has a strong connection with a decline in MSL capability. The reason why we interpreted as mentioned above is that there were significant vertical clearance differences during obstacle crossing among subjects even though subjects showing any balance or locomotor problems were not included in this study. Also, our findings are in agreement with our hypothesis, as well as results of previous studies that have reported that there is a strong correlation between MSL and dynamic balance, gait and mobility[19,20].

In addition, our experimental study clarified the mean of variance value of toe-obstacle clearance of the leading limb when stepping over an obstacle. Compared to the HMP subjects, LMP subjects exhibited a significantly larger variance value of toe-obstacle clearance of the leading limb when stepping over an obstacle (Table 1, 2). The mean of variance value of toe-obstacle clearance in LMP
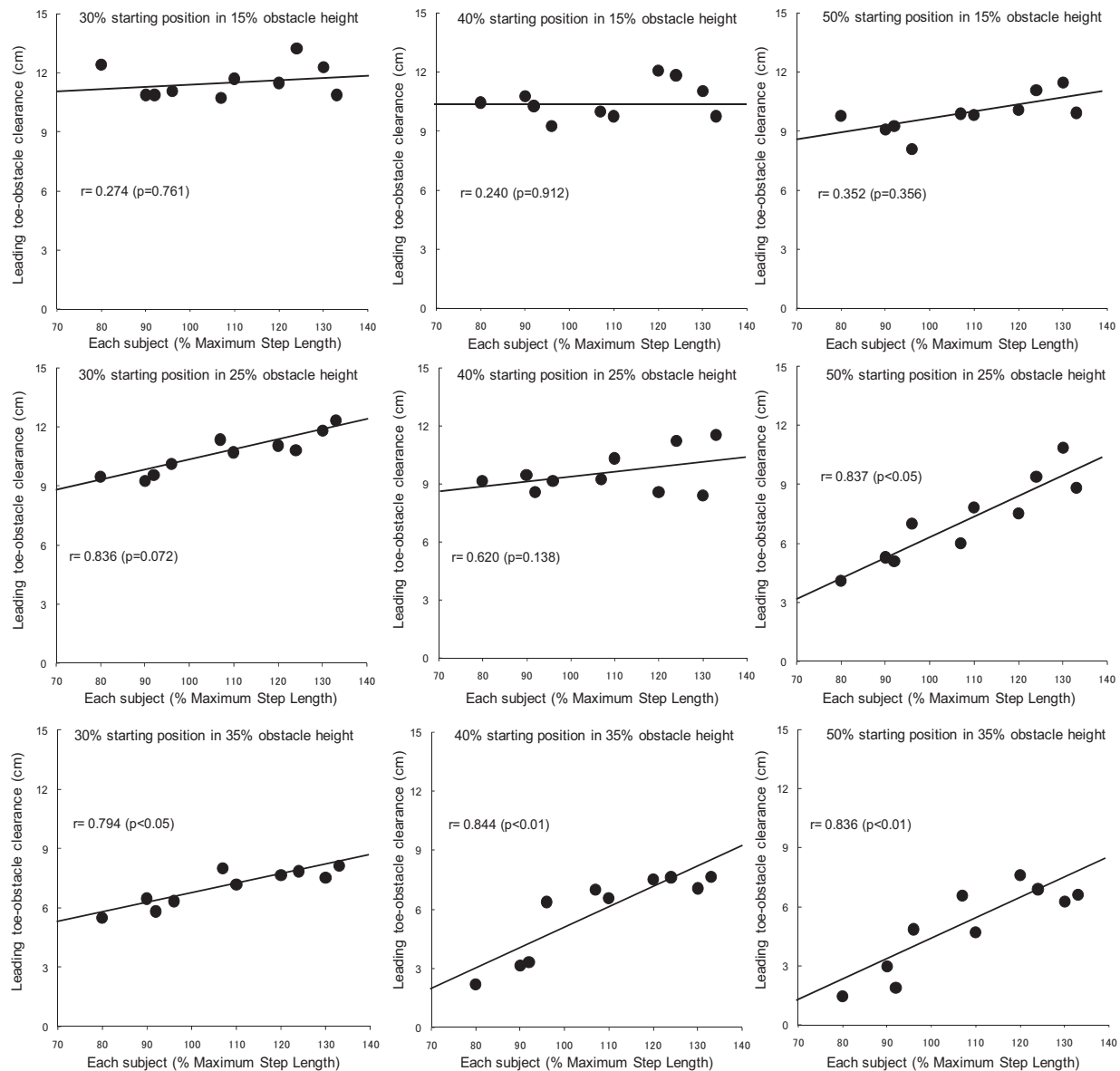
Fig 4.   The relationship between the MSL and the toe-obstacle clearance of the leading limb. The toe-obstacle clearance of the leading limb when stepping over an obstacle showed a significant correlation in the 50% starting position (25% obstacle height: r=0.837, p<0.05) and in the 30, 40, and 50% starting position (35% obstacle height: 30%, r=0.794, p<0.05, 40%, r=0.844, p<0.01, 50%, r=0.836, p<0.01).

subjects displayed significant differences during stepping over the higher obstacle from the far starting distance than HMP subjects. Showing a larger variance value of obstacle clearance of the leading limb during locomotion may reflect the fact that LMP subjects tend to have unstable approaching patterns. Interestingly, this phenomenon increased with more difficult strategies (a higher obstacle in 40%, 50% starting positions). This result suggests that LMP subjects may have a restricted adaptation capability to negotiate obstacles safely and to take the optimal trajectory. To our knowledge, the initiation of stepping from a quiet stance requires optimal limb trajectory using joint moments to achieve toe clearance and to predict the swing limb trajectory and must be considered simultaneously when stepping over an obstacle, unlike during unobstructed walking[14,15]. Therefore, the larger variation of

the mean of variance value of toe-obstacle clearance during approaching to an obstacle can be interpreted as a sign of an inappropriate foot trajectory control. Inappropriate joint moments of the stance limb and the trailing limb and restricted gait adaptation in response to the obstacle may perturb dynamic balance maintenance[13,21]. The observed outcomes in our present study are consistent with that of previous research showing that an increase in the swing foot excursion during obstacle crossing may be a result of dynamic instability, associated with restricted adaptation capability to operate the dynamic stability[13]. Furthermore, these findings showed some similarity in movement economy. In a previous work on the characteristic of gait, Sparrow, et al[3] report that the maximum obstacle clearance while minimizing modification to lower-limb trajectory is a good candidate control mechanism, and

such a control mechanism ensures maximum safety and minimizes the energetic cost of modifying the lower limb trajectory.

Our present study makes it clearly that the MSL capability and the approaching control ability during obstacle crossing has a remarkably close relation. Thus, a careful observation of the relationship between change patterns of obstacle clearance and MSL in multiple situations may support improved parameters to assess gait adaptation, and/or provide more complete information to understand the effects of obstacle height and MSL on obstacles crossing in healthy adults.

In conclusion, our results show that LMP subjects exhibited a significant smaller toe-obstacle clearance, a strong relationship between toe-obstacle and MSL, and a larger variance value of toe-obstacle clearance of the leading limb among all the subjects. The data are useful in understanding the relation of MSL and change patterns of obstacle clearance during crossing obstacles of different heights.

Acknowledgments

References

1) Begg RK and Sparrow WA. Gait characteristics of young and older Individuals negotiating a raised surface: Implications for the Prevention of Falls. J. Gerontol. A Biol. Sci. Med. Sci., 55: 147-154, 2000.

2) Gill J, Allum JHJ, Carpenter MG, Held-Ziolkowska M, Adkin AL, Honegger F and Pierchala K. Trunk Sway Measures of Postural Stability During Clinical Balance Tests: Effects of Age. J. Gerontol. A Biol. Sci. Med. Sci., 56: 438-447, 2001.

3) Sparrow WA, Shinkfield AJ, Chow S and Begg RK. Characteristics of gait in stepping over obstacles. Hum. Movement Sci., 15: 605-622, 1996.

4) Blake AJ, Morgan K, Bendall MJ, Dallosso H, Ebrahim SB, Arie TH, Fentem PH and Bassey EJ. Falls by elderly people at home: prevalence and associated factors. Age Ageing, 17: 365-372, 1988.

5) Campbell AJ, Borrie MJ, Spears GF, Jackson SL, Brown JS and Fitzgerald JL. Circumstances and consequences of falls experienced by a community population 70 years and over during a prospective study. Age Ageing, 19: 136-141, 1990.

6) Overstall PW, Exton-Smith AN, Imms FJ and Johnson AL. Falls in the elderly related to postural imbalance. Br Med. J., 1: 261-264, 1977.

7) Tinetti ME and Speechley M. Prevention of falls among the elderly. N. Engl. J. Med., 320: 1055-1059, 1989.

8) Chou LS and Draganich LF. Stepping over an obstacle increases the motions and moments of the joints of the trailing limb in young adults. J. Biomech., 30: 331-337, 1997.

9) Chou LS and Draganich LF. Increasing obstacle height and decreasing toe-obstacle distance affect the joint moments of the stance limb differently when stepping over an obstacle. Gait Posture, 8: 186-204, 1998.

10) Chen HC, Ashton-Miller JA, Alexander NB and Schultz AB. Stepping over obstacles: gait patterns of healthy young and old adults. J. Gerontol. A Biol. Sci. Med. Sci., 46: 196-203, 1991.

11) Gabell A and Nayak US. The effect of age on variability in gait. J. Gerontol. A Biol. Sci. Med. Sci., 39: 662-666, 1984.

12) Chou LS, Kaufman KR, Brey RH and Draganich LF. Motion of the whole body's center of mass when stepping over obstacles of different heights. Gait Posture, 13: 17-26, 2001.

13) Chou LS, Kaufman KR, Hahn ME and Brey RH. Mediolateral motion of the centre of mass during obstacle crossing distinguishes elderly individuals with imbalance. Gait Posture, 18:125-133, 2003.

14) Brunt D, Liu SM, Trimble M, Bauer J and Short M. Principles underlying the organization of movement from quiet stance. Gait Posture, 10: 121-128, 1999.

15) Brunt D, Santos V, Kim HD, Light K and Levy C. Initiation of movement from quiet stance: comparison of gait and stepping in elderly subjects of different levels of functional ability. Gait Posture, 21: 297-302, 2005.

16) Patla AE and Rietdyk S. Visual control of limb trajectory over obstacles during locomotion: effect of obstacle height and width. Gait Posture, 1: 45-60, 1993.

17) Simoneau GG, Cavanagh PR, Ulbrecht JS, Leibowitz HW and Tyrell RA. The influence of visual factors on falls-related kinematic variables during stair descent by older women. J. Gerontol. A Biol. Sci. Med. Sci., 46: 118-195, 1991.

18) Sparrow WA, Shinkfield AJ and Summers JJ. Gait characteristics in Individuals with mental retardation: unobstructed level walking, negotiating obstacles and stair climbing. Hum. Movement Sci., 17: 167-187, 1998.

19) Cho BL, Scarpace D and Alexander NB. Tests of stepping as indicators of mobility, balance, and fall risk in balance-impaired older adults. J. Am. Geriatr. Soc., 52: 1168-1173, 2004.

20) Medell J and Alexander N. A clinical measure of maximal and rapid stepping in older women. J. Gerontol. A Biol. Sci. Med. Sci., 55: 429-433, 2000.

21) Sparrow WA, Shinkfield AJ, Chow S and Begg RK. Characteristics of gait in stepping over obstacles. Hum. Movement Sci., 15: 605-622, 1996.