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Do Body Height and Leg Length Matter Equally? A Biomechanical Analysis of Obstacle Crossing in Young Adults

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Abstract Obstacle crossing is a fundamental locomotor task that requires adaptation of gait and postural control. Obstacle height is commonly normalized to an individual's anthropometrics, most often leg length, but some studies use body height. However, it remains unclear how these two reference measures influence gait outcomes. Therefore, this study examined the effects of using body height versus leg length as reference measures for obstacle height normalization on temporal-spatial gait parameters, postural control, and kinematics in young adults. Thirty-two young adults participated in a cross-sectional study. Participants performed obstacle crossing at 10%, 20%, and 30% of both leg length and body height. Temporal-spatial gait parameters, center of mass (COM) displacement and velocity, and hip, knee, and ankle angles were recorded using a 3D motion capture system. Repeated measure ANOVA was applied to test differences across obstacle heights within each normalization method. When normalized to body height, significant differences across obstacle heights were observed for crossing velocity, crossing time, trailing-limb crossing stride length, leading- and trailing-limb crossing stride time, and leading- and trailing-limb toe clearance, and hip, knee and ankle angles. In contrast, normalization to leg length revealed significant differences only in crossing time, trailing-limb crossing stride time, and leading- and trailing-limb toe clearance, and hip and knee angles. Neither normalization method showed significant effects on COM displacement or velocity. In conclusion, both normalization methods revealed similar overall trends, but body height normalization yielded a greater number of significant temporal-spatial gait changes compared to leg length normalization. These findings suggest that the choice of normalization method can influence the interpretation of gait outcomes and should be considered carefully in both research and clinical settings.

Keywords Obstacle Crossing, Postural Control, Body Height, Leg Length, Biomechanics

1. Introduction

Obstacle crossing is a crucial skill for daily life, as obstacles are commonly encountered in both indoor and outdoor environments [1,2]. The ability to adapt gait patterns to navigate these challenges is essential for maintaining safety and independence [3]. However, despite this adaptability, trips and falls commonly occur due to obstacles of varying heights—such as stair steps—found on surfaces like floors, sidewalks, carpet edges, electrical cords, and door thresholds [1,2]. When physical obstacles are combined with environmental hazards such as slippery floors, loose rugs, poor lighting, and cluttered walkways, the risk of falling increases significantly, especially when individuals must quickly respond to unexpected challenges along their path [4].

One key factor influencing gait during obstacle crossing is obstacle height itself. Obstacle height significantly affects temporal-spatial gait variables, kinematics, and the displacement of the center of mass (COM) during crossing in both young and older adults [5,6]. These effects can vary due to inter-individual anthropometric differences, such as leg length and overall body size [7]. To minimize inter-individual variability and enable more accurate comparisons, it has been suggested that obstacle heights be adjusted according to each participant's physical characteristics, most commonly leg length [8]. While leg length is the most used reference for standardizing, some studies have adopted body height as an alternative anthropometric measure [5].

When obstacle height was standardized relative to body height, increasing obstacle height resulted in linear increases in stride time and step width, a quadratic increase in stride length, and a linear decrease in gait velocity. Greater obstacle heights led to linear increases in the antero-posterior and vertical ranges of motion, as well as in peak mediolateral, upward, and downward velocities of the COM. However, the antero-posterior COM velocity at the point of maximum anterior COM–COP separation decreases linearly as obstacle height increases [5].

When obstacle height is normalized to leg length, increases in height significantly affect the vertical range of motion of the COM, with the highest COM position occurring as the swing toe clears the obstacle. In contrast, medio-lateral COM position and velocity showed less sensitivity to changes in obstacle height. Antero-posterior COM acceleration was more affected by obstacle height than its position and velocity. Additionally, crossing velocity decreased linearly as obstacle height rose [8].

Both body height and leg length standardizations result in similar overall trends during obstacle crossing, such as increased vertical COM motion and decreased crossing velocity with higher obstacles. However, subtle differences exist in how each reference influences specific movement characteristics. Although both leg length and body height are commonly used as references in gait research, it remains unclear how each influences movement characteristics and postural control during obstacle crossing, as no direct comparison has been performed. To our knowledge, no study has directly compared the impact of leg length versus body height standardization on temporal-spatial parameters, kinematics, and postural control during obstacle crossing in young adults. Therefore, this study aims to examine the effects of using body height versus leg length as reference points for various obstacle heights on temporal-spatial parameters and postural control in young adults. We hypothesize that there will be no significant differences in temporal-spatial parameters or postural control during obstacle crossing in young adults when obstacle height is normalized to body height versus leg length. Rather than determining which method is superior, the study seeks to explore how different anthropometric references may affect gait adaptations. The findings will help clarify the role of individual anthropometric characteristics in obstacle negotiation and may inform future research or clinical practices, such as the design of standardized obstacle clearance tests or tailored gait training programs for individuals with specific body proportions.

2. Materials and Methods

2.1. Study Design and Participants

A convenience sample of thirty-two young adults aged from 18 to 30 years was included in this cross-sectional study. Participants were included if they 1) were able to follow all aspects of the data collection process and 2) had a normal body mass index. Participants were excluded if they had a history of lower limb musculoskeletal disorders, current use of medications affecting balance, alcohol consumption within 24 hours before testing, vertigo or dizziness on the day of testing, uncorrectable visual impairments, or pain that interfered with posture or gait. This study was approved by the University Ethics Review Committee under the Human Projects Research ethics application (COA No.106/68). Before the trial, each participant signed a written informed consent form. Table 1 presents the characteristics of the participants.

Table 1. Characteristics of study participants (n = 32)

Characteristic	**Mean ± SD /n (%)**
Age (years); mean ± SD	26 ± 3.02
Gender; n (%)	
- Female	25 (78.12)
- Male	7 (21.88)
Weight (kg); mean ± SD	51.39 ± 8.70
Height (cm); mean ± SD	160.19 ± 6.04
Leg length (cm); mean ± SD	82.58 ± 3.31
Dominant leg; n (%)	
- Right	30 (93.75)
- Left	2 (6.25)

The sample size was determined by using G*Power version 3.1.9.2 (Heinrich Heine University Düsseldorf, Germany) based on an alpha level of 0.05, a power of 0.80, and an effect size of 0.25 for a repeated-measures ANOVA (within-subject factors). Depending on the conditions (10%, 20%, and 30%), there was one group and three measurements. The minimum number of participants needed is 28.

2.2. Procedure

Before the obstacle crossing task, demographic characteristics were collected from all participants, anthropometric measurements were taken, the dominant leg was identified, and reflective markers were attached. The anthropometric data included weight, height, leg length, and the distance between the anterior superior iliac spines (ASIS). The distance from the ipsilateral ASIS to the medial malleolus is measured as the leg length. The dominant leg was identified by having participants kick a ball, retrieve a small object from the floor using their foot, and trace a shape on the floor with their foot [9]. The leg used for at least two of these three tasks was considered as the dominant leg. [9]. Then, 29 reflective markers were attached to the body of participant according to Helen Hayes marker set model [10], with two extra markers placed at each end of the tube to mark the position of the obstacle. An eight-camera system (Raptor E, Motion Analysis Corporation, Santa Rosa, CA) operating at a sample rate of 120 Hz with a shutter speed of 1/1000 s, along with Cortex software version 8.2 was used to capture 3D marker motion data.

Participants were instructed to step over obstacles which were set up at 10%, 20%, and 30% of their leg length and body height. The obstacle heights were arranged in a random order. For each obstacle height, the task was repeated five times, with at least three trials in each condition requiring the use of the same leading leg for stepping over an obstacle. Participants were asked to look straight ahead while walking barefoot along the walkway and to cross over an obstacle placed in the middle section of the path. They were allowed to use their preferred leading limb to cross the obstacle. For each participant, the starting position was adjusted to ensure they achieved a steady, natural walking pace before approaching the obstacle, thus avoiding any rushed or slow movements. The mean (±SD) of the self-selected gait velocity during the approach phase before obstacle crossing was 1.15 ± 0.25 m/s. For the analysis, 3 successful trials were used. A successful trial of obstacle crossing was defined as the participant smoothly clearing the obstacle with both feet without any contact or displacement while maintaining balance and postural control throughout the task.

2.3. Data Processing

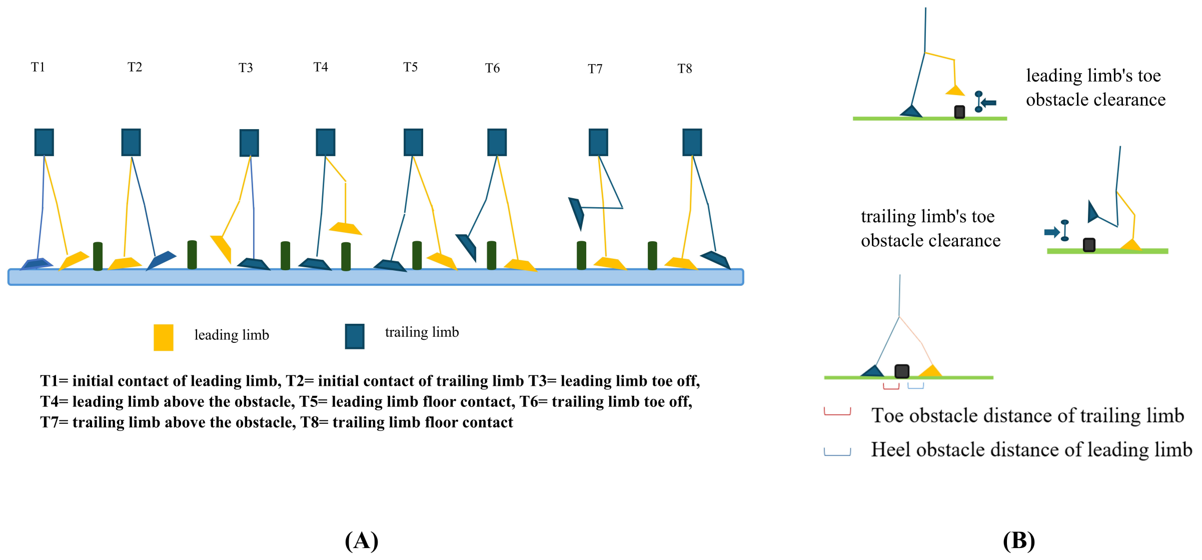
In this study, temporal-spatial gait parameters, COM displacement, and velocity, and kinematics were measured at eight time points (T1–T8), as shown in Figure 1A. T1 was the first contact of the leading foot and T2 was the trailing foot's first contact before the obstacle. T3 was the moment when the leading limb lifted from the ground to begin obstacle clearance. When the toe marker of the leading leg was directly above the obstacle, that time point was T4. T5 marked the landing of the leading limb beyond the obstacle. T6 occurred when the trailing leg raised off the ground. The toe reflective marker of the trailing leg was directly above the obstacle at T7 and T8 marked the landing of the trailing limb after clearance.

For temporal-spatial gait parameters including crossing velocity, crossing time, crossing stride length of both limbs, crossing stride time of both limbs, crossing stride width for the leading limb, toe obstacle clearance, toe obstacle distance, and heel obstacle distance were assessed. Crossing velocity was calculated using the distance and time taken between T2 (heel strike of trailing limb) and T8 (trailing limb floor contact). Crossing stride length and crossing stride time were measured from T1(heel strike of leading limb) to T5 (leading limb floor contact) for the leading limb, and from T2 (heel strike of trailing limb) to T8 (trailing limb floor contact) for the trailing limb. Crossing stride width of the leading limb was measured at T5 (leading limb floor contact). Toe obstacle clearance for both limbs was calculated as the vertical distance between the toe marker and the obstacle midpoint when the toe was above the obstacle [11]. Toe obstacle distance was measured as the horizontal distance from the leading and trailing foot's toe marker to the obstacle before crossing [11]. Heel-obstacle distance measured the horizontal distance from the heel marker of both feet to the obstacle after crossing (Figure 1B) [11].

For the postural control, the center of mass (COM) displacement and velocities (V) in the anteroposterior (AP), mediolateral (ML), and vertical directions were measured. COM displacement and velocity of the trailing limb were assessed during the leading limb's step over the obstacle (from T3: leading limb toe-off to T5: leading limb floor contact). Conversely, the leading limb was evaluated during the trailing limb's step (from T6: trailing limb toe-off to T8: trailing limb floor contact).

For the kinematic data, the hip, knee, and ankle angles in the sagittal plane of the leading and trailing limbs at T4 and T7 were reported. The angle between the pelvis segments and thigh segments was used to define the hip angle. The knee angle was described as the angle of thigh segments in relation to shank segments. The angle between shank and foot segments was measured for the ankle angle.

All data were exported to Cortex software version 8.2 and processed in MATLAB. To eliminate the impact of the body size, all temporal-spatial gait parameters and COM data for each testing condition were normalized using either the leg length or ASIS width of the subject.



T1= initial contact of leading limb, T2= initial contact of trailing limb T3= leading limb toe off, T4= leading limb above the obstacle, T5= leading limb floor contact, T6= trailing limb toe off, T7= trailing limb above the obstacle, T8= trailing limb floor contact

Figure 1. Data analysis of obstacle crossing task (A) Time points during obstacle crossing, (B) Toe obstacle clearance, toe-obstacle distance, and heel-obstacle distance of leading and trailing limb

2.4. Statistical Analysis

For statistical analysis, SPSS version 29.0 (SPSS Inc., 233 S Wacker Dr, 11th Fl, Chicago, IL 60606) was used with p value set at < 0.05. Normality was tested by using Shapiro-Wilk test, verifying a normal distribution. Results were presented as mean ±standard deviation. The differences of temporal-spatial parameters, postural control, and kinematics between conditions (10%, 20%, and 30%) in each standardization method were compared using a one-way repeated ANOVA with Bonferroni correction.

3. Results

3.1. Body Height

When obstacle height was normalized to body height, significant differences across obstacle heights were observed for crossing velocity, crossing time, trailing-limb crossing stride length, leading- and trailing-limb crossing stride time, and leading- and trailing-limb toe clearance (Table 2). Pairwise comparisons indicated that crossing time and crossing stride time for both limbs were highest in the 30% condition and lowest in the 10% condition. Conversely, toe obstacle clearance for both limbs was lowest in the 30% condition and highest in the 10% condition. Crossing velocity and leading limb crossing stride length were lower at 30% than at 10% and 20%. Obstacle height did not significantly affect COM displacement or velocity in any direction. For the kinematics, at the point that the leading limb was above the obstacle, significant differences across obstacle heights were observed for hip and knee angles of the leading limb. The 30% condition had the highest hip and knee flexion, whereas the 10% condition had the lowest hip and knee flexion. When the trailing limb was above the obstacle, significant differences in hip, knee, and ankle angles of the trailing limb, as well as the hip angle of the leading limb, were observed across different obstacle heights. The 30% condition showed the most hip and knee flexion for the trailing limb, while the 10% condition showed less flexion. In addition, the 20% and 30% conditions had higher ankle dorsiflexion than the 10% condition. For the leading limb, the 30% condition had more hip flexion than the 10% condition (Table 2).

3.2. Leg Length

When obstacle height was normalized to leg length, significant differences across obstacle heights were observed for crossing time, trailing-limb crossing stride time, and leading- and trailing-limb toe clearance (Table 3). Pairwise comparisons indicated that the crossing time and crossing stride time of the trailing limb in the 20% and 30% conditions were longer than in the 10% condition. In addition, toe obstacle clearance for both limbs in the 30% condition was lower than in the 10% and 20% conditions. Obstacle height did not significantly affect COM displacement or velocity in any direction. In the kinematics, when the leading limb was elevated over the obstacle, significant differences in hip and knee angles of the leading limb were detected across different obstacle heights. The 30% condition had the most hip and knee flexion, whereas the 10% condition demonstrated the least hip and knee flexion. Significant differences in the angles of the hip, knee, and ankle of the trailing limb were found when it was positioned above the obstacle, across various obstacle heights. In the 20% and 30% conditions, hip and knee flexion and ankle dorsiflexion angles are greater than in the 10% condition. (Table 3).

Table 2. Temporal-spatial gait and COM parameters when obstacle height was normalized to body height

Variable	**Obstacle height**			**$F_{(2,62)}$**	***p*-value**
	10%	**20%**	**30%**		
Temporal-spatial gait parameters					
Crossing velocity: cm/s	284.21 ±108.91	262.72 ±112.15	230.84 ±137.71 ^{a,b}	8.09	<0.01*
Crossing time: s	2.81 ±0.58	3.11 ±0.61^{a}	3.42 ±0.65 ^{a,b}	30.33	<0.01*
Leading limb					
Crossing stride length: cm	11.18 ±2.65	11.01 ±2.01	10.63 ±1.78	1.32	0.28
Crossing stride time: s	1.81 ±0.27	1.95 ±0.40 ^{a}	2.07 ±0.34 ^{a,b}	15.13	<0.01*
Crossing stride width: cm	4.08 ±1.27	4.19 ±1.57	4.35 ±1.42	0.80	0.45
Toe obstacle clearance: cm	2.46 ±0.62	1.96 ±0.52 ^{a}	1.68 ±0.46 ^{a,b}	28.25	<0.01*
Heel obstacle distance: cm	1.99 ±0.68	1.83 ±0.60	1.98 ±0.59	1.54	0.22
Trailing limb					
Crossing stride length: cm	10.58 ±2.61	10.60 ±2.08	9.82 ±2.53 ^{a,b}	3.95	0.02*
Crossing stride time: s	2.08 ±0.51	2.35 ±0.45 ^{a}	2.68 ±0.60 ^{a,b}	41.39	<0.01*
Toe obstacle clearance: cm	2.78 ±0.84	2.48 ±0.57 ^{a}	2.01 ±0.59 ^{a,b}	16.64	<0.01*
Toe obstacle distance: cm	2.06 ±0.91	2.12 ±0.95	2.31 ±0.69	2.05	0.14
Center of mass (COM) parameters					
Leading limb					
COM displacement: cm					
Anteroposterior	2.15 ±1.99	2.01 ±2.10	2.09 ±1.89	0.08	0.93
Mediolateral	0.27 ±0.35	0.24 ±0.28	0.30 ±0.34	0.62	0.54
Vertical	0.06 ±0.08	0.04 ±0.06	0.05 ±0.05	1.42	0.25
COM velocity: cm/s					
Anteroposterior	2.82 ±2.83	2.36 ±2.68	2.03 ±1.99	1.42	0.25
Mediolateral	0.34 ±0.47	0.26 ±0.32	0.27 ±0.29	0.66	0.52
Vertical	0.07 ±0.08	0.04 ±0.06	0.05 ±0.04	3.13	0.05
Trailing limb					
COM displacement: cm					
Anteroposterior	2.39 ±2.12	2.26 ±2.30	2.24 ±2.01	0.08	0.92
Mediolateral	0.37 ±0.41	0.27 ±0.29	0.46 ±0.51	2.96	0.06
Vertical	0.08 ±0.09	0.08 ±0.10	0.09 ±0.13	0.34	0.72
COM velocity					
Anteroposterior	3.13 ±3.04	2.69 ±2.99	2.22 ±2.13	1.56	0.22
Mediolateral	0.45 ±0.49	0.31 ±0.35	0.46 ±0.54	1.79	0.18
Vertical	0.09 ±0.12	0.09 ±0.12	0.09 ±0.13	0.07	0.93
Kinematics					
Leading limb					
Time point (T4): leading limb above obstacle					
Hip angle (degree) (flexion)	78.96 ±8.84	90.59 ±8.26 ^{a}	100.24 ±11.19 ^{a,b}	88.28	<0.01*
Knee angle (degree) (flexion)	105.06 ±10.00	118.09 ±7.22 ^{a}	122.75 ±6.09 ^{a,b}	66.64	<0.01*
Ankle angle (degree) (dorsiflexion)	75.91 ±8.35	78.56 ±7.74	77.11 ±17.34	0.54	0.58

Table 2 continued

Time point (T7): trailing limb above obstacle					
Hip angle (degree) (flexion)	17.88 ±7.05	19.47 ±6.92	21.17 ±8.72 [a]	6.97	<0.01*
Knee angle (degree) (flexion)	1.91 ±5.78	0.86 ±4.81	2.18 ±4.97	1.76	0.18
Ankle angle (degree) (dorsiflexion)	68.17 ±6.85	68.11 ±6.54	65.43 ±8.69	2.96	0.06
Trailing limb					
Time point (T4): leading limb above obstacle					
Hip angle (degree) (flexion)	4.99 ±7.34	4.79 ±6.54	3.00 ±7.96	2.99	0.06
Knee angle (degree) (flexion)	1.82 ±4.71	2.30 ±4.90	3.41 ±4.18	2.70	0.08
Ankle angle (degree) (dorsiflexion)	66.43 ±9.69	65.76 ±8.61	67.89 ±9.86	1.58	0.21
Time point (T7): trailing limb above obstacle					
Hip angle (degree) (flexion)	43.73 ±9.19	51.63 ±10.41 [a]	66.09 ±15.19 [a,b]	60.51	<0.01*
Knee angle (degree) (flexion)	114.31 ±17.09	132.31 ±6.21 [a]	137.42 ±4.96 [a,b]	48.57	<0.01*
Ankle angle (degree) (dorsiflexion)	64.51 ±15.91	74.33 ±12.76 [a]	74.87 ±22.71 [a]	5.20	<0.01*

Note: The data are presented by mean ±SD. * indicates significant differences between conditions;
[a] indicates a significant difference from the 10% condition, and [b] indicates a significant difference from the 20% condition.

Table 3. Temporal-spatial gait and COM parameters when obstacle height was normalized to leg length

Variable	**Obstacle height**			$F_{(2,62)}$	***p*-value**
	10%	**20%**	**30%**		
Temporal-spatial gait parameters					
Crossing velocity: cm/s	275.51 ±139.58	265.30 ±125.07	269.93 ±141.10	0.36	0.69
Crossing time: s	2.77 ±0.58	2.87 ±0.57 [a]	2.95 ±0.55 [a]	6.64	<0.01*
Leading limb					
Crossing stride length: cm	11.41 ±2.24	11.60 ±2.25	10.95 ±2.07	3.33	0.08
Crossing stride time: s	1.80 ±0.38	1.87 ±0.34	1.87 ±0.32	2.28	0.11
Crossing stride width: cm	3.89 ±1.23	3.94 ±1.42	3.89 ±1.57	0.04	0.96
Toe obstacle clearance: cm	2.61 ±0.66	2.47 ±0.65	2.09 ±0.43 [a,b]	15.12	<0.01*
Heel obstacle distance: cm	2.02 ±0.66	1.81 ±0.64	1.95 ±0.68	2.77	0.07
Trailing limb					
Crossing stride length: cm	10.50 ±2.32	11.00 ±2.45	10.38 ±2.15	3.28	0.05
Crossing stride time: s	2.03 ±0.42	2.13 ±0.45 [a]	2.20 ±0.46 [a]	9.73	<0.01*
Toe obstacle clearance: cm	2.85 ±0.68	2.92 ±0.78	2.51 ±0.67 [a,b]	6.39	<0.01*
Toe obstacle distance: cm	2.15 ±0.81	2.35 ±0.94	1.97 ±0.95	4.08	0.05
Center of mass (COM) parameters					
Leading limb					
COM displacement: cm					
Anteroposterior	1.78 ±1.83	2.26 ±2.28	2.24 ±1.96	0.94	0.39
Mediolateral	0.21 ±0.24	0.28 ±0.33	0.32 ±0.36	1.42	0.25
Vertical	0.05 ±0.07	0.05 ±0.06	0.06 ±0.07	0.21	0.81
COM velocity: cm/s					
Anteroposterior	2.35 ±2.57	2.93 ±3.23	2.72 ±2.52	0.63	0.54
Mediolateral	0.26 ±0.31	0.34 ±0.41	0.37 ±0.39	0.95	0.39
Vertical	0.06 ±0.08	0.06 ±0.06	0.06 ±0.07	0.07	0.93

Table 3 continued

Trailing limb					
COM displacement: cm					
Anteroposterior	2.82 ±2.83	2.36 ±2.68	2.03 ±1.99	1.04	0.36
Mediolateral	0.27 ±0.29	0.28 ±0.29	0.36 ±0.36	1.00	0.38
Vertical	0.06 ±0.08	0.06 ±0.08	0.09 ±0.09	2.69	0.08
COM velocity					
Anteroposterior	2.58 ±2.74	3.17 ±3.38	3.07 ±2.77	0.61	0.55
Mediolateral	0.34 ±0.37	0.35 ±0.39	0.41 ±0.41	0.33	0.73
Vertical	0.08 ±0.10	0.08 ±0.09	0.11 ±0.12	1.61	0.21
Kinematics					
Leading limb					
Time point (T4): leading limb above obstacle					
Hip angle (degree) (flexion)	72.09 ±8.93	79.69 ±8.92[a]	84.41 ±8.99[a,b]	69.67	<0.01*
Knee angle (degree) (flexion)	94.33 ±13.05	103.22 ±13.15[a]	113.22 ±9.67[a,b]	52.79	<0.01*
Ankle angle (degree) (dorsiflexion)	76.44 ±10.29	76.59 ±10.01	76.92 ±9.34	0.07	0.93
Time point (T7): trailing limb above obstacle					
Hip angle (degree) (flexion)	17.33 ±6.88	17.79 ±7.28	18.59 ±6.27	2.05	0.14
Knee angle (degree) (flexion)	1.99 ±6.18	1.87 ±5.41	1.58 ±5.22	0.14	0.87
Ankle angle (degree) (dorsiflexion)	67.90 ±8.00	68.39 ±7.01	67.49 ±8.56	0.38	0.68
Trailing limb					
Time point (T4): leading limb above obstacle					
Hip angle (degree) (flexion)	5.59 ±7.32	5.24 ±7.07	5.24 ±6.59	0.31	0.73
Knee angle (degree) (flexion)	1.74 ±4.82	2.90 ±5.46	1.96 ±4.71	1.31	0.27
Ankle angle (degree) (dorsiflexion)	66.52 ±8.46	66.45 ±9.15	67.29 ±8.06	0.57	0.57
Time point (T7): trailing limb above obstacle					
Hip angle (degree) (flexion)	40.78 ±8.64	45.59 ±9.63[a]	45.73 ±10.07[a]	15.1	<0.01*
Knee angle (degree) (flexion)	104.51 ±11.21	118.18 ±13.43[a]	122.63 ±12.47[a]	47.88	<0.01*
Ankle angle (degree) (dorsiflexion)	60.62 ±15.10	66.85 ±17.68[a]	69.59 ±15.22[a]	8.41	<0.01*

Note: The data are presented by mean ±SD. * indicates significant differences between conditions; [a] indicates a significant difference from the 10% condition, and [b] indicates a significant difference from the 20% condition.

4. Discussion

The present study evaluated the impact of using body height versus leg length as reference measures for obstacle height normalization on temporal and spatial gait parameters and postural control in young adults. The findings revealed that the two normalization methods resulted in different effects of obstacle height on temporal-spatial gait parameters in young adults. However, no significant differences were observed in COM displacement or velocity when obstacle heights were standardized to either body height or leg length.

When obstacle height was normalized to body height, significant differences across obstacle levels were observed for crossing velocity, crossing time, trailing-limb crossing stride length, leading- and trailing-limb crossing stride time, and leading- and trailing-limb toe clearance. Normalization to leg length yielded significant differences only for crossing time, trailing-limb crossing stride time, and leading- and trailing-limb toe clearance. This discrepancy likely arises because normalizing to body height produces relatively greater obstacle levels than normalizing to leg length. Higher relative obstacle heights impose greater demands on locomotor adjustments, which likely explains why more spatiotemporal parameters differ with body-height normalization [5].

In this study, crossing time increased with rising obstacle height, reaching its maximum duration at 30% of both body height and leg length. Obstacle height significantly influenced the crossing time regardless of normalization by body height or leg length. Crossing time increased progressively with obstacle height for both methods, indicating greater caution and longer planning to prevent tripping [12]. However, the two normalization methods showed different sensitivity patterns. Normalization by body height revealed significant crossing time differences at all obstacle heights, indicating a smooth progression of task difficulty. In contrast, leg length normalization showed significant differences only between 10% and the higher obstacles (20% and 30%), with no difference between 20% and 30%. This suggested that normalization by body height is more sensitive to detecting subtle variations across all obstacle heights, whereas normalization by leg length better distinguishes between low and high difficulty levels. To the best of our knowledge, no prior studies have directly compared these two normalization methods in obstacle crossing. This study provides new insights, highlighting that the choice of normalization method can influence interpretation of temporal-spatial parameters.

At the same time, toe clearance for both the leading and trailing limbs decreased with increasing obstacle height, regardless of whether the obstacle height was based on body height or leg length. To our knowledge, this was the first study to observe this pattern. The reduced clearance might reflect a strategy to minimize unnecessary vertical foot movement while still ensuring safe crossing over higher obstacles. The combination of longer movement time and lower toe clearance suggested that crossing higher obstacles required greater motor control and careful attention. Participants likely adopted a cautious movement strategy to maintain balance, conserve energy, and achieve sufficient clearance during obstacle negotiation [12].

Another temporal-spatial parameter affected by the obstacle height was crossing speed. A previous study had shown that young adults reduce their gait velocity when crossing higher obstacles [13]. In our study, young adults crossed higher obstacles at a slower speed, but this decrease was only significant when obstacle height was adjusted based on body height, not when scaled to leg length. This difference likely occurs because obstacles based on body height were relatively taller than those based on leg length, increasing task difficulty and leading young adults to adopt a slower walking strategy.

This increase in stride time in young adults was consistent with the results reported by Chou [13]. The longer stride time, along with the increased movement time, suggested that participants adjusted their gait by lengthening stride duration to ensure safer clearance. Together, slower crossing speed and longer stride time indicated a cautious walking strategy that emphasized stability and safety when negotiating more challenging obstacles.

For center of mass displacement and velocity, there were no significant effects when the obstacle height was standardized to body height and leg length. This suggested that healthy young adults were able to maintain overall dynamic stability while crossing obstacles, even as stride time and crossing speed were adjusted. One possible explanation is that participants relied on temporal-spatial gait adaptations, such as prolonging stride time, rather than altering their COM trajectory to ensure safe clearance. This supported earlier research showing that young adults keep good control of their COM when facing small to moderate obstacles [14].

For kinematics, the leading limb's hip and knee flexion increased significantly as obstacle height increased, whether normalized by body height or leg length. The greatest hip and knee flexion at the 30% condition compared to the least at 10%, confirmed that participants adjusted their movements to ensure safe obstacle clearance and reduce the risk of tripping. This finding aligned with a previous study showing that higher obstacle heights required increased hip and knee flexion to maintain sufficient toe clearance. As obstacle height increased, participants flexed their hip and knee joints more to keep toe and heel clearance relatively constant [15], demonstrating precise motor control strategies that promoted stability and successful obstacle negotiation.

When the trailing toe was positioned above the obstacle, normalized either by body height or leg length, the trailing limb exhibited increased hip, knee, and ankle flexion. Although its joint kinematics resembled that of the leading limb, the trailing limb depended more on proprioceptive feedback and motor planning due to limited visual input during crossing [16,17]. This reliance likely contributes to greater joint flexion, serving as a compensatory strategy to ensure adequate clearance and reduce the risk of tripping.

The findings of this study have important implications for clinical practice. By comparing the effects of obstacle height, standardized body height versus leg length on postural control and temporal-spatial parameters, physical therapists and rehabilitation specialists can better understand how these different reference measures influence gait performance. This knowledge can aid in designing safer and more personalized obstacle negotiation tasks, especially for older adults at higher risk of falls. Additionally, standardizing obstacle height based on individual body proportions allows for fairer comparisons across individuals and supports more targeted training interventions to reduce fall risk. Furthermore, determining whether body height or leg length serves as a more valid standard contributes to the development of a unified framework for obstacle-crossing research. The findings also provide insights into how anthropometric factors influence locomotor strategies during obstacle negotiation, demonstrating that individuals modify temporal-spatial parameters while maintaining stable center of mass control despite variations in obstacle height. A major limitation of this study is the uneven gender distribution, with 78% of participants being female, which may limit the generalizability of the results. In addition, the present findings were derived from a general young adult population; therefore, the results may not fully generalize to high-performance athletes. Athletes typically exhibit superior balance control, greater muscle strength, enhanced motor anticipation, and increased joint flexibility, which may reduce variability in center of mass displacement. However, sport-specific biomechanical adaptations could result in distinct movement strategies that influence gait parameters. Future studies should therefore include athletic populations, as well as individuals with neuromuscular or musculoskeletal disorders, to determine how enhanced or impaired motor control affects postural stability during obstacle negotiation. Furthermore, although this study compared normalization based on body height and leg length, it did not account for their ratio. From a biomechanical perspective, the leg length-to-height ratio may alter the relative demands of obstacle crossing, and future research should investigate its influence on gait adaptations and balance control.

5. Conclusions

This study found that normalizing obstacle height by body height versus leg length affected temporal-spatial gait parameters differently, although both methods showed similar general patterns. Despite these differences, center of mass control remained consistent, suggesting that young adults relied primarily on adjusting their stride to maintain safe clearance. These results emphasize the significance of choosing suitable anthropometric references for gait analysis in both research and clinical settings.

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