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# Original Article

# Estimated lower speed boundary at which the walk ratio constancy is broken in healthy adults

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**Abstract.** [Purpose] The ratio of step length to cadence (walk ratio) is invariant over a wide range of speeds. However, no studies have investigated details of the change in the walk ratio at slow speeds. It is necessary to explore how walking behavior changes at a low speed to understand the slow walking observed in various conditions such as aging and pathological conditions. In this study, changes in the walk ratio at slow speeds were investigated, and a lower boundary was estimated at which the walk ratio constancy is broken. [Subjects and Methods] Twenty-one healthy adults were instructed to walk along a flat, straight walkway at five different speeds (fast, preferred, slightly slow, slow, and very slow). The walk ratio was calculated from the step length and cadence. [Results] As the walking speed decreased, the walk ratio and variance began to increase abruptly. The initial break in the walk ratio constancy was at approximately 62 m/min. In addition, the boundary of cadence was approximately 98 m/steps/min. [Conclusions] The study successfully determined a lower boundary at which the walk ratio constancy was broken, suggesting that different control strategies are used when walking at less than the gait speed at which constancy is broken in healthy adults. The finding provides valuable information for understanding slow walking observed in individuals with various pathological conditions.

Key words: Gait analysis, Step, Cadence

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### **INTRODUCTION**

Walking speed is calculated by multiplying the step length by cadence, for which infinite combinations exist at a certain speed. However, a single ratio of step length and cadence is selected based on the minimal cost of transfer<sup>1</sup>). This walk ratio<sup>2</sup>) remains constant within a certain range of speeds, including the preferred speed<sup>3, 4</sup>). At fast speeds, the walk ratio undergoes a transition from walking to running. However, details of change in the walk ratio at slow speeds remain to be explored. Sekiya et al. demonstrated that as walking speed decreases, the walk ratio increases and becomes more variable<sup>5</sup>). They hypothesized a boundary at which the walk ratio constancy would be broken during slow walking; however, they did not identify a specific speed. It is necessary to explore how walking behavior changes at a low speed to understand the slow walking observed in various conditions such as aging and pathological conditions such as stroke. Herein, the basic characteristics of slow walking at various speeds were examined, and the lower walking speed boundary was estimated at which the walk ratio constancy is broken in healthy adults.

# **SUBJECTS AND METHODS**

Twenty-one healthy volunteers (11 men, 10 women) participated. The mean age, height, and weight (± standard deviation)

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Gait parameter	Speed condition					
	Very slow	Slow	Slightly slow	Preferred	Fast	
Step length (m)	$0.43\pm0.16$	$0.47\pm0.15$	$0.58\pm0.089$	$0.70\pm0.071$	$0.87\pm0.094$	
Cadence (steps/min)	$24.8\pm13.4$	$42.0\pm17.7$	$83.2\pm13.2$	$112.1\pm7.37$	$135.9\pm12.5$	
Speed (m/min)	$11.4\pm8.14$	$20.9\pm12.5$	$49.1\pm13.0$	$\textbf{79.0} \pm \textbf{9.88}$	$118.2\pm18.6$	
Walk ratio (m/steps/min)	$0.027\pm0.029$	$0.015\pm0.012$	$0.0071 \pm 0.0012$	$0.0063 \pm 0.00071$	$0.0064 \pm 0.00081$	
Adjusted step length $(m)^*$	$0.43\pm0.16$	$0.47\pm0.15$	$0.58\pm0.091$	$0.70\pm0.071$	$0.87\pm0.070$	
Adjusted cadence (steps/min)*	$24.8\pm13.3$	$41.9\pm17.6$	$83.2\pm13.3$	$112.0\pm 6.33$	$135.7 \pm 12.1$	
Adjusted speed (m/min)*	$11.4\pm8.14$	$20.9\pm12.6$	$49.1\pm13.1$	$79.0\pm10.0$	$118.2\pm17.6$	
Adjusted walk ratio (m/steps/min)*	$0.027\pm0.029$	$0.015\pm0.012$	$0.0071 \pm 0.0012$	$0.0069 \pm 0.00047$	$0.0064 \pm 0.00053$	
Participants classified in the slow-walk cluster, n (%)	21 (100%)	19 (90.5%)	4 (19.0%)	0 (0%)	0 (0%)	

Table 1. Gait parameters and number of participants classified in the slow-walk cluster for each speed condition

Data are shown as means ± standard deviations unless otherwise indicated. \*Each gait parameter is adjusted for height

were  $24.5 \pm 3.3$  years,  $166.7 \pm 8.2$  cm, and  $59.2 \pm 10.2$  kg, respectively. Exclusion criteria were a gait disability and recent lower extremity injury. The study protocol was approved by the Ethics Committee of Tokyo Bay Rehabilitation Hospital, and informed consent was obtained from all participants.

Participants were verbally instructed to walk in a straight line on a flat walkway at five different speeds (fast, preferred, slightly slow, slow, and very slow). Speed conditions were such that participants could walk at their preferred speed as a reference before increasing or decreasing the speed: 1) preferred, 2) fast, 3) preferred, 4) slightly slow, 5) preferred, 6) slow, and 7) very slow. Participants were instructed to walk comfortably, and they were given no instructions regarding the step length or cadence. Three experimenters (A, B, and C) participated in the measurements. Experimenters A and B visually observed and marked the fifth and fifteenth heel strikes after walking was initiated. The resulting 10-step distance was measured in centimeters. Experimenter C recorded the time required to walk 10 steps using a stopwatch with 1/100-second precision.

The step length, cadence, speed, and walk ratio (step length/cadence) at each speed condition were calculated individually using the distance walked and time required. For the preferred speed, the mean of three measurements was used. To exclude the influence of height differences, gait parameters were adjusted using the following equations<sup>5</sup>): adjusted step length = step length × (mean height / individual height); adjusted cadence = cadence × (individual height / mean height)<sup>1/2</sup>; adjusted speed = adjusted step length × adjusted cadence; and adjusted walk ratio = adjusted step length / adjusted cadence.

A K-means algorithm based non-hierarchal cluster analysis was used to divide all the data for the two variables (speed and walk ratio) into two clusters (normal walk and slow walk), enabling us to evaluate the lower walking speed boundary. Pearson correlation coefficients with Bonferroni correction were used to examine the relationships between each gait parameter in each cluster. All statistical analyses were performed using STATA/SE 13.1 (StataCorp, College Station, TX, USA). A p-value <0.05 was considered statistically significant.

## **RESULTS**

Gait parameters at each speed condition with or without height adjustment are shown in Table 1. A non-hierarchal cluster analysis successfully divided the data of the two variables (speed and walk ratio) into two clusters (Fig. 1-A). The maximum speed in the slow-walk cluster was 61.1 m/min, and the minimum speed in the normal-walk cluster was 63.6 m/min; thus, the clusters were divided at approximately 62 m/min without overlap (Fig. 1-A).

Figure 1-B shows the relationship between the step length and cadence; these variables were clearly correlated in the normal-walk cluster but not in the slow-walk cluster. Despite a slight overlap, the clusters could be clearly separated in terms of cadence. The average of these overlapping values (six values, three per cluster) was 98.0 m/steps/min. However, the data could not be clearly divided into two clusters in terms of the step length.

Table 2 shows the correlation coefficients between each gait parameter in each cluster. In the normal-walk cluster, the walk ratio was independent (i.e., it had no correlation with other gait parameters). In contrast, the walk ratio correlated negatively with speed (r=-0.47; p<0.001) and cadence (r=-0.58; p<0.001) in the slow-walk cluster. The step length, cadence, and speed significantly correlated with each other in both clusters.

#### DISCUSSION

This is the first investigation of walking characteristics over several speeds, including a very slow speed (<20 m/min). This study's results showed an initial break in walk ratio constancy at approximately 62 m/min in healthy adults; this loss of constancy subsequently increased as speed decreased. Additionally, the findings suggested that the walk ratio boundary was



Fig. 1. Relationships between the velocity and walk ratio (A), and between the step length and cadence (B).

	Adjusted speed	Adjusted step length	Adjusted cadence	Adjusted walk ratio
(A) Slow-walk cluster				
Adjusted speed	1.00			
Adjusted step length	$0.71^{*}$	1.00		
Adjusted cadence	$0.95^{*}$	$0.50^{*}$	1.00	
Adjusted walk ratio	$-0.47^{*}$	-0.16	$-0.58^{*}$	1.00
(B) Normal-walk cluster				
Adjusted speed	1.00			
Adjusted step length	$0.95^{*}$	1.00		
Adjusted cadence	$0.95^{*}$	$0.80^{*}$	1.00	
Adjusted walk ratio	0.03	0.35	-0.29	1.00

Table 2. Pearson correlation coefficients between each gait parameter in each cluster

\*Bonferroni corrected p values <0.001

defined by cadence not by step length. Accordingly, a cadence boundary was estimated at approximately 98 m/steps/min.

On the basis of scatter plot observations, Sekiya et al. suggested that the walk ratio tended to increase and vary more at  $\leq 60 \text{ m/min}^{5)}$ , which was consistent with our results. Furthermore, the disrupted walk ratio constancy at slow speeds may be explained by a model-based assumption in which the physical constraints for optimizing energetic efficiency are no longer preserved at slow walking speeds. A physics-based model with an energy efficiency of 100% proposed that an upper swing phase limit was 0.5-0.6 seconds<sup>6</sup>), resulting in a lower cadence limit of approximately 100–120 m/steps/min without consideration of the double-support phase. This model-based lower boundary of energy-efficient walking is consistent with our results.

A few reports have pointed out that the behaviors of the walk ratio in patients with pathological conditions are different from that of healthy person. A stroke is the representative condition of slow walking, as stroke patients walk at decreased speeds (6–48 m/min)<sup>7</sup>). Suzuki et al. demonstrated that although the walk ratio of patients with hemiparetic stroke with a slow walking speed (<60 m/min) was approximately one-half of the walk ratio of healthy subjects, this ratio remained constant regardless of speed<sup>8</sup>). Their report suggests that patients with hemiparetic stroke differ from healthy subjects in terms of incorporating a slow walking strategy. Rota et al. examined the walk ratio in patients with multiple sclerosis; the walk ratio was significantly lower in these patients than in control patients, and it was related to the severity of disability<sup>9</sup>). They suggested that the walk ratio is a disability-sensitive index of gait control, and thus a promising outcome measure for treatments. Further studies are needed to clarify the difference between walk ratios corresponding to normal and various pathological gaits, and the clinical meaning of them.

This study has several limitations. First, a visual method was used to identify the point of heel strike. Although the findings drawn from this study may be robust even with a several cm bias, this may have caused slight differences in our boundary calculations. Second, as only temporal-distance factors were investigated in this preliminary study, further studies are required to explore the true mechanism that defines the lower walking boundary. Finally, a relatively small sample size of patients with a narrow age range was used. A larger sample size and wide age range of patients are needed to explore whether there is a difference between age groups and between genders.

In conclusion, this study confirmed that the walk ratio constancy was broken at slow speeds in healthy adults. The gait speed at which the walk ratio constancy was broken was estimated as 62 m/min, suggesting that walking at less than approximately 60 m/min may be regulated with somewhat different control strategies than those used at the higher walking speed in healthy adults. The present study's findings offer valuable information for understanding slow walking observed in individuals with various pathological conditions.

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