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Reliability of Evaluation Parameters of Ground Reaction Force in Stepping Motion

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Abstract The purpose of this study was to 1) examine the reliability of the evaluation parameters of the ground reaction force (GRF) in the stepping motion among middle-aged and elderly people, and 2) calculate the number of steps required for the analysis of the stepping motion. Participants were 128 middle-aged and elderly individuals regularly exercising at a health promotion facility. Participants performed 3 trials of the stepping motion for 10 seconds at the optimum speed on the same spot. We used a force plate to measure the vertical GRF during the stepping motion. The number of cycles and spatiotemporal parameters (8 mechanical parameters, 6 temporal parameters) were evaluated from the waveform of the GRF. Results showed that the number of cycles in the stepping motion was higher in the 2nd and 3rd trials than in the 1st trial, and the intraclass correlation coefficients (ICC) were as high as .837 for men and .840 for women. When comparing the two consecutive steps of 10 steps after the start of the stepping motion, the stepping motion was in a steady state from the 3rd step because the difference between the two steps became smaller after the 3rd step. Furthermore, when the number of steps required to ensure reliability was calculated using the ICC (1, 1) of each parameter, it was shown that 15 or more steps were required. Our results suggested that stepping motion may be able to secure high reliability with a smaller number of steps than gait.

Keywords Gait, Spatiotemporal Parameter, Intraclass Correlation Coefficients, Middle-aged and Elderly People

1. Introduction

In general, the physical function starts to decline with aging. Equilibrium, lower limb muscle strength, and instantaneous power were particularly found to be declined as well [1]. The maintenance and improvement of these physical functions can contribute to preventing long-term care for the elderly. Gait ability has been used as an evaluation of fall risk [2] and death risk [3]; therefore, maintaining the gait ability is necessary to maintain a good quality of life. The 10-meter walk test [4], the 6-minute walk test [5], and the timed up & go test [6] are used to evaluate gait function. Another reliable method to evaluate gait ability has been by an accelerometer [7], a force plate, and a motion capture system [8].

Gait is a movement with periodicity and left-right symmetry, so its variability and symmetry can be evaluated as parameters using the GRF waveform [9,10]. The variability of the temporal parameters of stride, swing, and stance time is a distinguishable parameter between falls and non-falls. On the other hand, variability in step width, stride time, and speed was considered to be a distinguishable parameter between elderly and young individuals [9]. In addition, Kim and Eng [10] investigated the symmetry of the vertical GRF during gait in stroke patients. Therefore, GRF is most often applied as the gold standard parameter to determine gait-related parameters in the absence of standardization of predictors [11], it would be possible to extract the gait characteristics of each subject from the GRF waveform.

On the other hand, the issue is that the evaluation of gait ability requires a large space and imposes a burden on the participants. Therefore, gait ability and dynamic balance ability have been evaluated by stepping motion similar to gait [12,13]. Stepping motion is defined as alternating steps with the left and right foot in the same place, and stepping motion was used in accordance with the metronome sound, and gait ability and dynamic balance ability were found to be low if the error between the metronome sound and the timing of contact with the foot was large [12,13]. These studies focused only on temporal parameters, and although the contact timing of the stepping motion can be evaluated, mechanical parameters such as the load during the stepping motion have not been evaluated. Previous studies [10,14] have reported that mechanical parameters during gait in stroke and knee osteoarthritis patients differ from healthy subjects, and the most commonly applied GRF to determine gait-related parameters [11] from the study is necessary. In fact, as there has been less evidence on stepping motion analysis than gait analysis, the reliability of measurement methods and evaluation variables has not been yet clarified. The purpose of this study was to examine the reliability of the stepping motion and calculate the number of steps required for the analysis by the mechanical and temporal parameters of the GRF.

2. Materials and Methods

2.1. Participants

One hundred twenty-eight middle-aged and elderly individuals (56 men: 64.0 ± 10.4 years; 72 women: 60.9 ± 9.1 years) who regularly exercised at a health promotion facility. The descriptive data of participants were shown in Table 1. Participants were administered sufficient oral and written explanations of the purpose of the study and measurement. Informed written consent was obtained from all participants. The Ethics Committee of Nekoyama Miyao Hospital approved this study (Ref. No. 2017-NR-010; 2020-NR-001).

2.2. GRF in Stepping Motion

The stepping motion was measured by the force plate (BM-220, TANITA Co., Ltd. Tokyo, Japan) [15,16]. The sampling rate was 80 Hz, and the vertical GRF (kgf) during the stepping motion was recorded on a computer. Participants took a standing posture on the force plate and performed three trials of the stepping motion for 10 seconds at the participant's optimum speed on the same spot. Although stepping motions for 20 seconds were performed in previous studies [12,13], the duration was set to 10 seconds for reducing the burden on the participants in this study. Therefore, the number of stepping motions was different for each participant. The width of the left and right foot was set to the width of the waist, the raising of the foot and the swing of the upper limbs were arbitrary for the participant, and the line of sight was directed forward as much as possible.

2.3. GRF Parameters

The vertical GRF of walking showed a bimodal waveform [17]. Therefore, the peak values of the two main peaks and the valley during the stepping motion were defined as the peak value of the 1st peak (F1), the valley (F2), and the 2nd peak (F3). The peak values of F1 to F3 were standardized by body weight. One cycle was the stepping motion from contact to the next contact of the ipsilateral foot. As for the parameters of the GRF, eight variables of mechanical parameters (F1, F2, F3, M shaped, asymmetry (AS)-F1, AS-F2, AS-F3, AS-M shaped) and six variables of temporal parameters (FT1, FT2, FT3, AS-FT1, AS-FT2, AS-FT3) were evaluated like the previous studies [17, 18] (Figure 1). If the value of the M shape was small, a clear bimodal waveform was drawn, and if the value was close to zero, the symmetry was evaluated as having small laterality. FT was the time between F1 and F3 in two consecutive cycles on the left and right. If the value was small, the tempo of the stepping motion was fast.

Table 1. Descriptive data

	Men (*n* = 56)	Women (*n* = 72)	*p* value	*ES* (Cohen's *d*)
Age(year)	64.0±10.4	60.9±9.1	.074 †	.322
Height(m)	1.69±0.06	1.55±0.05	< .001 †	2.638
Weight(kg)	73.4±13.6	59.0±10.3	< .001	1.226
BMI(kg/m^2)	25.6±4.2	24.6±4.2	.120	.238

Paired t-test: †

ES (Effect Size) .20 < *d*: small, .50 < *d*: medium, .80 < *d*: large

2.4. Data Analysis

Shapiro-Wilk's test was performed to confirm the normality of descriptive data of the participants. If the data were normally distributed, paired t-tests were performed. If the data were not normally distributed, Mann-Whitney U-test was performed to examine the sex differences. The effect size (Cohen's *d*) was calculated to examine the magnitude of the differences. Intraclass correlation coefficients (ICC) were calculated for each sex in the 1st-2nd trials and the 2nd-3rd trials to examine the inter-trial reliability in the number of cycles of stepping motion. The ICC defined 0.81 and above as Almost Perfect [19]. In addition, the two-way ANOVA for two independent factors (sex x trial) was performed to compare the difference between the 3 trials. A multiple comparison test was performed using the Tukey HSD method if a significant interaction or the main effect was observed. The effect size (η^2) was calculated to examine the magnitude of the differences. Based on these results, we decided on which trial to be analyzed using 14 parameters (eight mechanical and six temporal parameters) of the GRF.

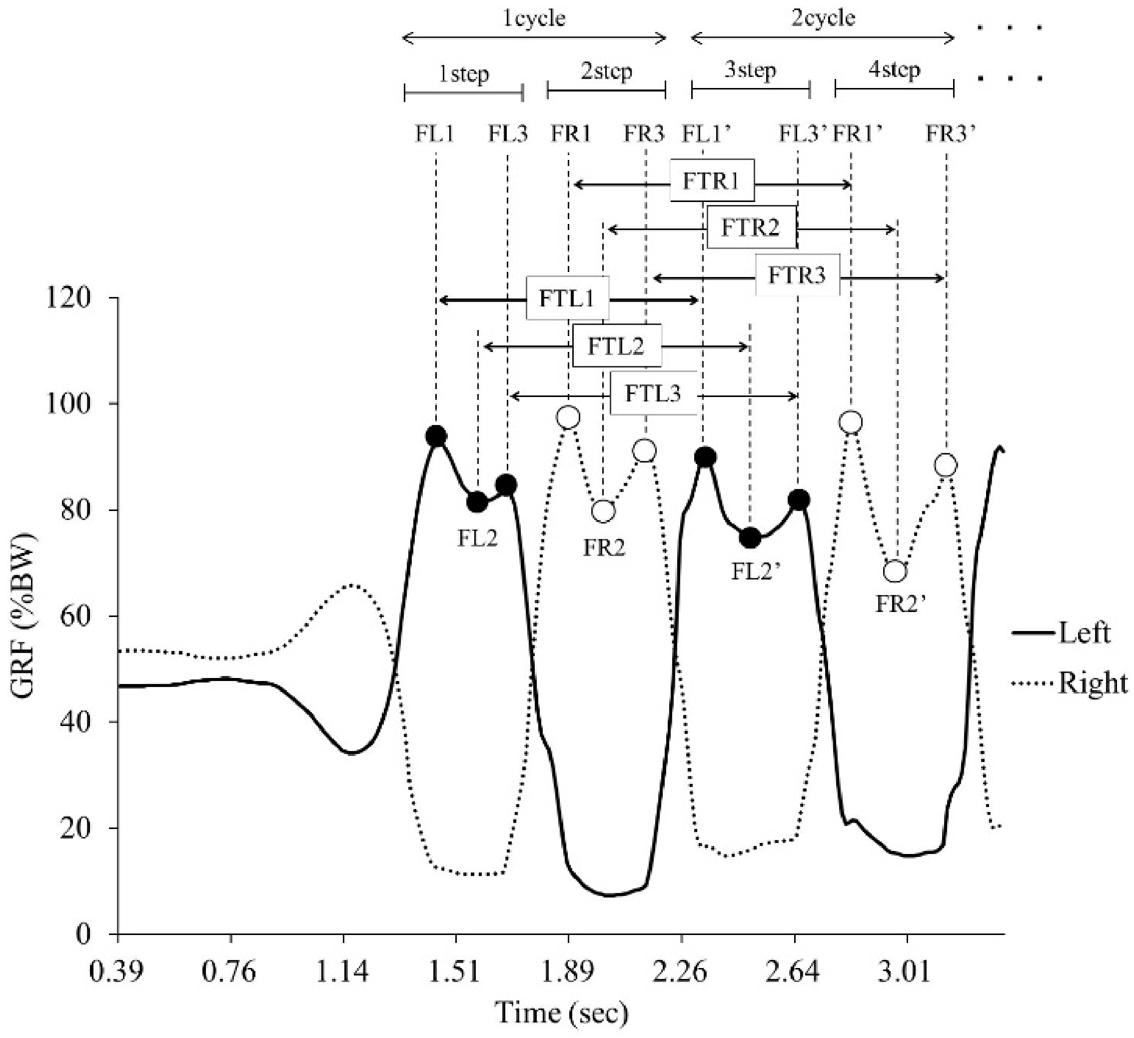

Figure 1. Calculation of mechanical parameters and temporal parameters by the GRF waveform

Mechanical parameters (8 parameters)

F1: 1st peak GRF, F2: valley peak GRF, F3: 2nd peak GRF, M shaped = (F1/F2 + F3/F2) / 2, AS-F1 = (|FL1−FR1| / 0.5×(FL1＋FR1)) × 100, AS-F2 = (|FL2−FR2| / 0.5×(FL2＋FR2)) × 100, AS-F3 = (|FL3−FR3| / 0.5×(FL3＋FR3)) × 100, AS-M shaped = (|ML shaped−MR shaped| / 0.5 × (ML shaped＋MR shaped)) × 100

Temporal parameters (6 parameters)

FT1 = F1'time−F1time, FT2 = F2'time−F2time, FT3 = F3'time−F3time, AS-FT1 = (|FTL1−FTR1| / 0.5 × (FTL1＋FTR1)) × 100, AS-FT2 = (|FTL2−FTR2| / 0.5 × (FTL2＋FTR2)) × 100, AS-FT3 = (|FTL3−FTR3| / 0.5 × (FTL3＋FTR3)) × 100,

GRF: Ground Reaction Force, AS: Asymmetry, FL: Force Left, FR: Force Right, ML shaped: Left M shaped, MR shaped: Right M shaped

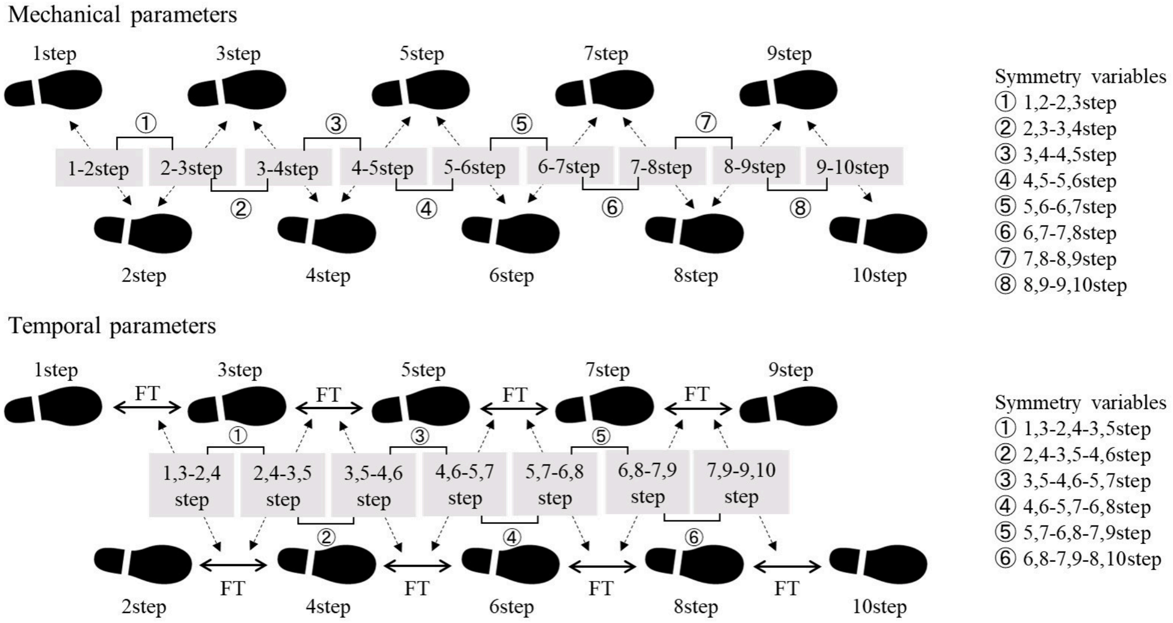

Figure 2. Calculation of mechanical parameters and temporal parameters in 10 steps (5 cycles) after the start of stepping motion

We analyzed 10 steps (5 cycles) after the start of the stepping motion to calculate the number of steps required to evaluate the stepping motion. The mechanical parameters were compared using 2 consecutive steps (1-2 steps, ... 9-10 steps), and the temporal parameters were compared using 4 consecutive steps (1,3-2,4 step, ...7,9−8,10 step) (Figure 2). The mechanical parameters of symmetry were then compared using 3 consecutive steps (1,2-2,3 step, ... 8,9-9,10 step), and the temporal parameters of symmetry were compared using 5 consecutive steps (1,3-2,4-3,5 steps, ...6,8-7,9-8,10 step) (Figure 2). The normality of the data was confirmed by the Shapiro-Wilk test. If the data were normality, paired t-tests was performed and if the data were not normality, Mann-Whitney U-test was performed. We calculated the ICC (1, 1) for each parameter to evaluate its reliability. The ICC (1, 1) calculated the number of steps required to guarantee Almost Perfect (ICC > .81) using the Spearman-Brown formula. All analyses were conducted using R for Windows, Version 2.11.1. Statistical significances were set at $p < .05$ in all analyzes.

3. Results

Table 2 shows the inter-trial reliability of the number of cycles in the stepping motion and the results of the two-way ANOVA for the two factors (sex x trial). The ICC (1, 1) in the 1st and 2nd trials were .626 for men and .641 for women, and the ICC (1, 1) for the 2nd and 3rd trials were .837 for men and .840 for women. The two-way ANOVA showed no significant main effect on sex ($p = .600$), and a significant main effect was observed in the trial ($p < .001$). When a multiple comparison test was performed, the number of cycles in the 2nd and 3rd trials was larger than those in the 1st trial ($p < .001$). No interaction was observed ($p = .851$). From these results, the average value of the 2nd and 3rd trials for the analysis of the GRF parameters was selected.

Table 2. The result of the reliability of the number of cycles and two-way ANOVA (sex x trial) in stepping motions

Parameter		Trial 1	Trial 2	Trial 3	ICC (1, 1) (95%CI)		sex		trial		interaction (*ES*)
					Trial 1, 2	Trial 2, 3	main effect (*ES*)	post-hoc	main effect (*ES*)	post-hoc (Tukey HSD)	
Cycle	Men (n = 56)	6.8±1.3	7.6±1.3	7.9±1.2	.626 (.437-.762)	.837 (.737-.901)	.600 (.001)		< .001 (.133)	< .001 (1trial < 2,3trial)	.851 (.001)
	Women (n = 72)	6.8±1.4	7.8±1.3	8.0±1.3							

ES (Effect Size) .01 < η^2: small, .06 < η^2: medium, .14 < η^2: large

Table 3 shows the results of comparing the mechanical and temporal parameters of 10 steps after the start of the stepping motion. Normality was confirmed for only 2 steps in F1, 3 steps in F2, and 7 steps in F3 for the mechanical parameters, and for 2 sections in FT1, 1 section in FT2, and 1 section in FT3 for the temporal parameters. Regarding the mechanical parameters, many parameters had a significant difference between the two consecutive steps in the first half. In particular, the effect size comparing 1-2 step and 2-3 step was moderate (r = .328-.432). In addition, the symmetry of the mechanical parameters showed no significant difference between the two consecutive steps. On the other hand, the temporal parameters were significantly different between FT1, FT3, and AS-FT1; however, the effect size was small (r = .180-.275).

Table 4 shows the reliability of the mechanical and temporal parameters from the 3rd step onward, based on the results of two consecutive steps shown in Table 3. The ICC (1, 1) of the mechanical parameters had an M shape of Almost Perfect (ICC = .823), while the other parameters were Fair to Substantial (ICC = .386-.654). On the other hand, the ICC (1, 1) of the time parameter was as high as Substantial to Almost Perfect (ICC = .797-.812) for FT1 to FT3, but the symmetry of the temporal parameters was Fair to Moderate (ICC = .321-.449). For the ICC (1, 1) of all parameters to satisfy 0.81 or higher, it was necessary to analyze 7 intervals (3-11 steps) with mechanical parameters and 10 intervals (3-15 steps) with temporal parameters.

Table 3. Comparison of the mechanical and temporal parameters

		1-2 step	2-3 step	3-4 step	4-5 step	5-6 step	6-7 step	7-8 step	8-9 step	9-10 step
Mechanical parameters	F1	< .001* (.432)	.652 (.040)	.034* (.188)	.866 (.015)	.091 (.150)	.219 (.109)	.198 (.114)	.193 (.115)	.181 (.119)
	F2	.948 (.006)	< .001* (.328)	.122 (.137)	.045* (.177)	.363 (.081)	.576 (.050)	.839 (.018)	.920 (.009)	.658 (.039)
	F3	.002* † (.276)	.241 (.104)	.017* (.211)	.461 † (.065)	.289 † (.094)	.959 (.005)	.479 (.063)	.136 † (.133)	.241 (.104)
	M shaped	< .001* (.336)	< .001* (.348)	.161 (.124)	.044* (.177)	.006* (.241)	.365 (.080)	.139 (.131)	.195 (.114)	.011* (.225)
		1,2-2,3 step	2,3-3,4 step	3,4-4,5 step	4,5-5,6 step	5,6-6,7 step	6,7-7,8 step	7,8-8,9 step	8,9-9,10 step	
	AS-F1	.199 (.114)	.847 (.017)	.551 (.053)	.966 (.004)	.363 (.081)	.763 (.027)	.321 (.088)	.894 (.012)	
	AS-F2	.956 (.005)	.372 (.079)	.898 (.011)	.893 (.012)	.501 (.060)	.392 (.076)	.806 (.022)	.468 (.064)	
	AS-F3	.674 (.037)	.613 (.045)	.668 (.038)	.385 (.077)	.838 (.018)	.381 (.078)	.709 (.033)	.923 (.009)	
	AS-M shaped	.697 (.035)	.075 (.158)	.734 (.030)	.107 (.143)	.981 (.002)	.777 (.025)	.517 (.057)	.527 (.056)	

		1,3-2,4 step	2,4-3,5 step	3,5-4,6 step	4,6-5,7 step	5,7-6,8 step	6,8-7,9 step	7,9-8,10 step
Temporal parameters	FT1	.138 (.131)	.037* (.185)	.414 (.072)	.326 (.087)	.400 (.075)	.202 (.113)	.120 (.138)
	FT2	.842 (.018)	.190 (.116)	.086 (.152)	.056 (.169)	.114 (.140)	.130 (.134)	.085 (.152)
	FT3	.452 (.067)	.023* (.201)	.082 (.154)	.148 (.128)	.018* (.209)	.010* (.228)	.062 (.165)
		1,3-2,4-3,5 step	2,4-3,5-4,6 step	3,5-4,6-5,7 step	4,6-5,7-6,8 step	5,7-6,8-7,9 step	6,8-7,9-8,10 step	
	AS-FT1	.002* (.275)	.152 (.127)	.157 (.125)	.339 (.085)	.034* (.188)	.269 (.098)	
	AS-FT2	.118 (.139)	.958 (.005)	.998 (.000)	.554 (.052)	.216 (.109)	.539 (.054)	
	AS-FT3	.981 (.002)	.245 (.103)	.353 (.082)	.495 (.061)	.500 (.060)	.235 (.105)	

Upper row: *p* value, Lower row: *ES*

Paired t-test: †

ES (Effect Size) .10 < *r*: small, .30 < *r*: medium, .50 < *r*: large; .20 < *d*: small, .50 < *d*: medium, .80 < *d*: large

**p* < .05

Table 4. Reliability of the mechanical and the temporal parameters

Mechanical parameters (3-10 step)				Temporal parameters (3-4 step - 9-10 step)			
	ICC (1, 1)	95%CI	k		ICC (1, 1)	95%CI	k
F1	.621	.555-.688	3	FT1	.797	.750-.839	2
F2	.654	.591-.717	3	FT2	.805	.761-.846	2
F3	.443	.372-.521	6	FT3	.812	.769-.852	1
M shaped	.823	.782-.861	1				
AS-F1	.386	.313-.467	7	AS-FT1	.449	.372-.532	6
AS-F2	.386	.313-.467	7	AS-FT2	.384	.307-.468	7
AS-F3	.405	.332-.486	7	AS-FT3	.321	.247-.406	10
AS-M shaped	.406	.333-.487	7				

k: The number of steps required to guarantee ICC (1, 1) Almost Perfect of .81 or higher using the Spearman-Brown formula

4. Discussion

The purpose of this study was to 1) examine the reliability of the evaluation parameters of the ground reaction force (GRF) in the stepping motion among middle-aged and elderly people, and 2) calculate the number of steps required for the analysis of the stepping motion. Results showed that the number of steps in the stepping motion was higher in the ICC in the 2nd and 3rd trials than in the ICC in the 1st and 2nd trials and that the 2nd and 3rd trials were found to be more reliable. ICC is a coefficient that indicates how much the measured values of the same subject match when measured multiple times and has been considered to be Almost Perfect when the value was .81 or higher [19]. In the present study, the ICC in the 2nd and 3rd trials were .837 for males and .840 for females, and .81 or higher for males and females. In addition, the two-way ANOVA showed that the number of cycles of stepping motion in the 2nd and 3rd trials was significantly larger than those in the 1st trial, and no sex difference was observed. Previous studies on gait conducted the 1st trial as a warm-up trial and evaluated it using the data of the 2nd and 3rd trials [20, 21]. Fransen et al. [22] also performed gait analysis on 41 patients with knee osteoarthritis and reported that it was more reliable to use the 2nd and 3rd trials than the 1st and 2nd trials. Furthermore, Demura et al. [12] showed no sex difference in various stepping motions. This study confirmed these findings, and it is possible to extract highly reliable stepping motions by using the 1st of the 3 trials as the practice trial and the 2nd and 3rd trials as the main trial regardless of sex.

In comparison with the two consecutive steps of the stepping motion, a significant difference was observed at the start of the stepping motion, such as the 1st step and the 2nd step, and the 2nd step and the 3rd step of the mechanical parameters. Those with reduced gait ability are considered to have greater variability at the start of gait and movement [23]. Therefore, it has been clarified that a steady gait is generally used for gait analysis, and it takes 3.5 to 5.2 steps or 2.5 meters to reach a steady gait [24, 25]. Strutzenberger et al. [26] demonstrated that a sloping gait was also considered a steady gait at the 3rd step. From the results of this study, it is considered that the stepping motion includes unstable motion at the start of the motion as well as gait, and the steady stepping motion is after the 3rd step.

On the other hand, there was a significant difference in the temporal parameters between two consecutive steps. However, the effect size was small. Therefore, the stepping motion might be at a constant speed immediately at the beginning. Temporal parameters such as gait cadence and contact time were significantly different between the 1st and 2nd steps and the 2nd and 3rd steps [26]. This was a contradictory result to this study. In addition, the ratio of the brake and propulsive impulse of the GRF in the front-rear direction was measured at the same time as the temporal parameters, and a significant difference was observed between the 1st step and the 2nd step [26]. Therefore, it is considered that the forward propulsive force required for gait has an influence, and the number of steps required for the temporal parameters to reach a steady-state differs between the gait and stepping motion. The above would suggest that the stepping motion in the steady-state could be evaluated from the viewpoint of mechanical and temporal parameters by analyzing the 3rd and subsequent steps.

The ICC of the mechanical and the temporal parameters after the 3rd step was different for each parameter. It suggested that the reliability of the mechanical parameters was higher in the M shape (calculated using F1 to F3) than in the individual parameters of F1 to F3. If the value of the M shape was small, a clear bimodal waveform was drawn, and it was evaluated that the gait ability was high [17]. In addition, knee osteoarthritis or walking slowly led to an indistinct bimodal waveform [27, 28]. Therefore, the present study indicated that the M shape was reliable and could be a valid parameter. As mentioned, the temporal parameters had stepped at a constant speed immediately after the start of the stepping motion, so it is considered that the ICC was also high, and the variable was highly reliable.

On the other hand, the symmetry of the mechanical and temporal parameters had a low ICC, and it took many steps to guarantee reliability. Byun et al. [20] showed that the ICC of the gait parameter was 0.85 or more when the cadence and step time was 4 steps or more, but the asymmetry of the step time required 24 steps or more. Motti Ader et al. [29] also reported that although the ICC was .90 or higher in 6 steps with general gait parameters (i.e., average stance time, average stride time, average swing time, average step time, average double support, average single support, average stride length, average stride speed), the parameters for evaluating gait asymmetry (stride time asymmetry, step time asymmetry) could not be highly reliable within 32 steps. This study clarified that the symmetry of the mechanical parameters required 11 steps or more and the symmetry of the temporal parameters required 15 steps or more, and the symmetry parameters required a large number of steps as in the previous study. Therefore, it was suggested that the number of steps required to ensure the reliability of the stepping motion might differ depending on the parameters. However, it was speculated that the reliability of the stepping motion parameters in this study could assure a smaller number of steps than the reliability of the gait parameters.

Several limitations should be noted. First, the number of steps analyzed was small. We focused on the stepping motion to reduce the burden on the participant; therefore, we set the stepping motion for only 10 seconds. We found that 15 steps or more would be required to evaluate the symmetry parameters. Future studies should examine the trial time and the number of cycles of the stepping motion. Secondly, the relationship with gait ability was not examined. Although the reliability of the stepping motion in the present study was equivalent to the reliability of gait ability shown in the previous study, the criteria-related validity has not been confirmed. Examining the relationship between the stepping motion and the gait ability could show the effectiveness of the stepping motion, and future studies can examine this matter.

5. Conclusions

High reliability was obtained regardless of sex by analyzing the 3rd and subsequent steps using the 2nd and 3rd trials of the stepping motion. It was also shown that more than 15 steps would be required to evaluate all the parameters in this study. Therefore, the stepping motion may be able to secure high reliability with a smaller number of steps than gait.

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