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RESEARCH PAPER

Reliability and validity of a force-instrumented treadmill for evaluating balance: A preliminary study of feasibility in healthy young adults☆

Zhou Yuntao, PT, MS [a,b,*], Izumi Kondo, MD, PhD [c], Masahiko Mukaino, MD, PhD [a], Shigeo Tanabe, PT, PhD [d], Toshio Teranishi, PT, PhD [d], Takuma Ii, PT, MS [e], Kensuke Oono, MS [f], Soichiro Koyama, PT, PhD [d], Yoshikiyo Kanada, PT, PhD [d], Eiichi Saitoh, MD, PhD [a]

[a] *Department of Rehabilitation Medicine I, School of Medicine, Fujita Health University, Toyoake, Japan*
[b] *School of Rehabilitation Medicine, Nanjing Medical University, Nanjing, China*
[c] *Department of Rehabilitation Medicine, National Center for Geriatrics and Gerontology, Ohbu, Japan*
[d] *Faculty of Rehabilitation, School of Health Sciences, Fujita Health University, Toyoake, Japan*
[e] *Department of Rehabilitation, Fujita Health University Hospital, Toyoake, Japan*
[f] *Fujita Memorial Nanakuri Institute, Fujita Health University, Tsu, Japan*

KEYWORDS
balance evaluation;
computerized dynamic posturography;
EquiTest;
instrumented treadmill

Abstract *Background:* With the development of computer technology, computerized dynamic posturography provides objective assessments of balance and posture control under static and dynamic conditions. Although a force-instrumented treadmill-based balance assessment is feasible for balance evaluations, currently no data exists.
Objective: This study was undertaken to assess the reliability and validity of balance evaluations using a force-instrumented treadmill.
Methods: Ten healthy adults participated in evaluations using both the treadmill and the EquiTest. Four balance evaluations were conducted: Modified Clinical Test of Sensory Interaction on Balance, Unilateral Stance, Weight Bearing Squat, and Motor Control Test.
Results: All balance evaluations using the force-instrumented treadmill method shared good reliability (intraclass correlation coefficient ≥0.6). The Modified Clinical Test of Sensory Interaction on Balance, Unilateral Stance, and Weight Bearing Squat evaluations had a correlation

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* Corresponding author. School of Rehabilitation Medicine, Nanjing Medical University, Number 140, Hanzhong Road, Nanjing, China.
E-mail address: tychezhou@126.com (Z. Yuntao).

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of $r < 0.5$ with EquiTest, whereas the Motor Control Test balance evaluation had moderate correlations ($r > 0.5$) with the EquiTest.

Conclusion: The results demonstrated that all balance evaluations using the force-instrumented treadmill were reliable, and that the Motor Control Test evaluation was moderately correlated with the EquiTest. Therefore, the use of a force-instrumented treadmill in balance evaluations might provide a certain level of value to clinical practice.

Introduction

With the marked increase in the aging population, falls in the elderly are becoming a serious problem for our society. Fall-related injuries, for example, femoral neck fractures or vertebral compression fractures, limit the activities of daily living and influence mortality rates in the elderly [1,2]. It has been reported that balance impairment is one of the major causes of falling in the elderly [3,4]. For example, increases in the range of postural sway in the medial—lateral direction are associated with increased fall risks [5]. A review focused on fall screening assessment reported a correlation between the scores on balance assessment scales, such as the Berg Balance Scale and the Step Test, and the risk of falling [6]. Thus, it is quite important to develop useful balance assessment tools and improve the evaluations of balance so as to prevent serious fall-related injuries.

A variety of assessment tools focusing on balance evaluation have been developed and validated [7,8]. Recently, with the development of computer technology, a new kind of evaluation has been used in clinical practice—computerized dynamic posturography [9—11]. Computerized dynamic posturography is a highly specialized, noninvasive assessment technique used to measure the adaptive mechanisms of the central nervous system, and to objectively quantify and differentiate among the wide variety of possible sensory, motor, and central adaptive impairments to balance control. Good examples of this technique can be found in the stabilograph [12], accelerometer [13], three-dimensional motion analysis system [14], and EquiTest [15—19].

The EquiTest provides objective assessments of balance and posture control under static and dynamic conditions [15—19]. The assessments are focused on functional balance evaluations, which are used to assess the entire range of balance and fall risks. The system is composed of computers, a suspension system for safety, a tiltable board covering the field of view, and a force platform for kinesiological analysis. The EquiTest has been developed for years, and has been used mainly for cases of dizziness in the head and neck or otolaryngology surgery [20] and for balance feature comparisons of fall and nonfall group balance cases [21]. The EquiTest has demonstrated good reliability and validity in previous studies [22,23].

A force-instrumented treadmill has recently been used in gait training [24—28]. Controlled movements of the treadmill's belt, and a handrail and/or suspension are beneficial for easy and safe gait training. In addition, the force-instrumented treadmill can easily obtain feedback information of ground reaction force during clinical gait evaluation and training. Furthermore, because the whole system can be set under the floor of rehabilitation exercise rooms, it has a high degree of usability for gait disorders. Although a treadmill-based balance assessment created by modifying the method of the EquiTest is feasible, no data exists to demonstrate that the force-instrumented treadmill can make such balance evaluations. As a preliminary evaluation of feasibility, the present study aimed to assess the reliability and validity of the force-instrumented treadmill compared with the EquiTest for standard standing balance evaluations in healthy young adults.

Materials and methods

Participants and experimental protocols

Ten healthy volunteers participated in this study. Prior to the present study, the required sample size was estimated according to a power analysis for the intraclass correlation coefficient (ICC). Based on previous studies [29,30], assumed ICC, assumed power level, and Type I error were set to 0.7, 0.7, and 0.05, respectively. Power analysis indicated that 10 participants would be needed to demonstrate the underlying reliability and validity of the force-instrumented treadmill for evaluating balance. All participants gave informed written consent, and the protocol was approved by the University Clinical Research Committee. Each participant was evaluated for balance function on both the force-instrumented treadmill (FTM-1200WA; Tec Gihan, Kyoto, Japan) (Figure 1) and the EquiTest (MPS-3102; NeuroCom, Clackamas, USA) (Figure 2). The participants were randomly divided into two groups; one was evaluated first with the force-instrumented treadmill and then 3 days later with the EquiTest, and the other was first evaluated with the EquiTest and then with the treadmill. Standard EquiTest assessments were used for both the force-instrumented treadmill evaluations and the EquiTest. The assessments consisted of four balance evaluations: the Modified Clinical Test of Sensory Interaction on Balance (mCTSIB), the Unilateral Stance (US), the Weight Bearing Squat (WBS), and the Motor Control Test (MCT).

Experimental setup

In the force-instrumented treadmill assessments, the apparatus consisted of a treadmill, a firm surface (Balance Master; NeuroCom) in different environmental conditions, a board covering for vision feedback, and a suspension clamp

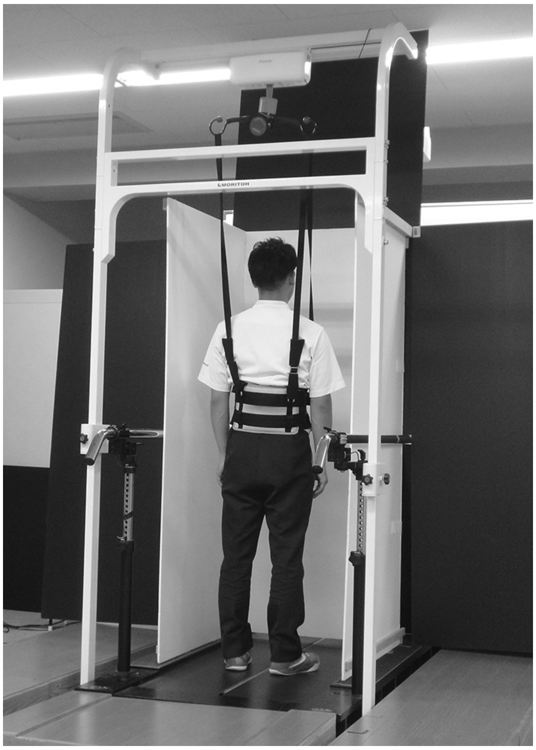

Figure 1. Force-instrumented treadmill.

system (SP-1000; Moritoh, Ichinomiya, Japan) for safety. An A/D converter (NI DAQ USB-6229; National Instruments, Austin, USA) and LabVIEW2013 (National Instruments) were used for collecting and analysing data. Data were sampled

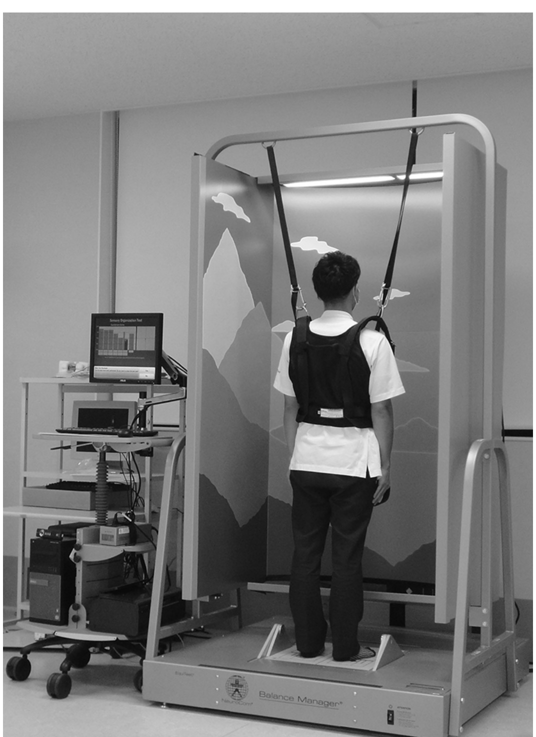

Figure 2. EquiTest.

at 500 Hz. Two force plates were used to measure the centre of pressure, which is defined by movements of the centre of gravity (COG). The force plate with the amplifier produces six voltage outputs that represent the mechanical inputs in $Fx \times Fy \times Fz \times Mx \times My \times Mz$ for each platform, where $Fx \times Fy \times Fz$ is the medial–lateral force $\times$ anterior–posterior force $\times$ vertical force on the left or right platform. $Mx \times My \times Mz$ is the plate moment about the $X \times Y \times Z$ axes. We determined the $X \times Y$ coordination of force application point on both platforms (*xL, xR, yL, yR*) using the following equations:

$$xL = \frac{-(MyL - FxL \times az0)}{FzL} + \frac{p}{4} \tag{1}$$

$$yL = \frac{(MyL + FyL \times az0)}{FzL} \tag{2}$$

$$xR = \frac{-(MyR - FxR \times az0)}{FzR} - \frac{p}{4} \tag{3}$$

$$yR = \frac{(MyR + FyR \times az0)}{FzR} \tag{4}$$

where $az0$ is the thickness (characteristic value) and p is the width of the force plate. The locations x, y of the COG can be determined according to the following equations:

$$x = \frac{xR \times FzR + xL \times FzL}{FzL + FzR} \tag{5}$$

$$y = \frac{yR \times FzR + yL \times FzL}{FzL + FzR} \tag{6}$$

In EquiTest assessments, a firm surface (Balance Master; NeuroCom) was used in different environment conditions. A coloured board covering (NeuroCom) was used for vision feedback. A suspension clamp system (NeuroCom) was used to prevent falling. Data were sampled at 100 Hz, and data collection and analysis were performed using standard software accompanying the EquiTest.

Balance evaluations

Measurements to evaluate balance function consisted of four balance evaluations. In all measurement conditions, the participants were asked to have their arms hanging along the side of their body, their feet parallel, and a 10 cm distance between their heels. If the participants failed to maintain balance, the test was stopped and one more trial was added if possible.

The test protocol for the mCTSIB objectively identified abnormalities in the participant's use of the sensory systems (somatosensory, visual, and vestibular) that contribute to postural control. The participants were evaluated under four conditions (three 20-second trials each): eyes open with firm surface, eyes closed with firm surface, eyes open with foam surface, and eyes closed with foam surface. The US test (three 20-second trials each) quantified postural sway velocity with the participant standing on either the right or the left foot on the force plate, with eyes open or closed. During the WBS assessment (three 2-second trials each), the participants were instructed to maintain equal weight on both legs while standing erect and then to squat in three positions of knee flexion (30°, 60°, and 90°). The percentage of body weight borne by each leg was measured at each of the three knee flexion positions and while erect (0°). The MCT assessed the ability of the autonomic motor system to quickly recover following an unexpected external disturbance in forward or backward movements. This test was conducted under four conditions based on different perturbations: (1) backward movement with medium disturbance; (2) backward movement with large disturbance; (3) forward movement with medium disturbance; and (4) forward movement with large disturbance. Medium and large disturbances were characterized by duration and amplitude [0.3 s and 1.74% of body height (cm), and 0.4 s and 3.13% of body height (cm), respectively].

Data analyses

All balance scores in the present study were calculated according to the equation in the EquiTest user guide. The mCTSIB used two indexes to evaluate the balance function, the equilibrium score (ES) and the strategy score (SS). The ES quantified the postural stability calculated using the COG sway during the four sensory conditions. For the ESs, the participants exhibiting little sway achieve an ES near 100, while those approaching their limits of stability achieve an ES near zero. The SS can be used to quantify the ankle and hip movements that a participant uses to maintain balance during each 20-second trial. A score near 100 indicates that the participant predominately uses ankle strategy to maintain balance, while a score near 0 shows that the participant predominantly uses hip strategy. The US used one index for evaluation, the mean COG sway velocity (MS), which represents the COG stability while the participant stands independently on each leg with eyes open or closed. In the WBS test, weight symmetry (Sym) was used to calculate the balance function. In the MCT evaluation, two indexes for evaluation, Sym and reaction time (RT), were used. The RT was calculated as the time between translation (stimulus) onset and initiation of the participant's active response (force response in each leg).

Statistical analyses

To assess the reliability of the force-instrumented treadmill, the ICC [1,2] of the test–retest was used. The ICC score was interpreted as follows: sufficient ($>$0.7), acceptable (0.4–0.7), and poor ($<$0.4) [29,30]. The validity of the treadmill test was determined by calculating the correlation coefficient, absolute error, and relative error between the treadmill test and EquiTest results, for which measurements are known to be highly valid [22]. Absolute error was calculated by subtracting scores obtained on the EquiTest from those obtained on the force-instrumented treadmill. Relative error was calculated by dividing the absolute error by the EquiTest score. A statistical analysis was performed using Spearman's rank correlation coefficient (r). The r values were interpreted as follows: $r < 0.20$, weak correlation; $r = 0.20$–0.35, slight correlation; $r = 0.35$–0.65, moderate correlation; $r = 0.65$–0.85, good correlation; and $r = 0.85$–1.0, very good correlation [31]. SPSS software (version 19; SPSS, Chicago, IL, USA) was used for statistical analyses.

Table 1 Reliability of the Modified Clinical Test of Sensory Interaction on Balance in the instrumented treadmill test.

	Condition		ICC
	Vision	Surface	
ES	EO	Firm	0.62
	EC	Firm	0.72
	EO	Foam	0.62
	EC	Foam	0.61
SS	EO	Firm	0.88
	EC	Firm	0.84
	EO	Foam	0.96
	EC	Foam	0.90

EC = eyes closed; EO = eyes open; ES = equilibrium score; Firm = firm surface; Foam = foam (unstable) surface; ICC - = intraclass correlation coefficient; SS = strategy score.

Results

None of the participants failed to maintain balance during assessment of both the treadmill test and the EquiTest.

Test–retest reliability of the force-instrumented treadmill

Tables 1–4 show the test–retest reliability of various tests assessed using the force-instrumented treadmill. In the mCTSIB evaluation, the ESs exhibited acceptable reliability (Table 1; ICCs ranged from 0.61 to 0.72), while the SSs demonstrated higher reliability (ICCs ranged from 0.84 to 0.96). The MS scores of the US evaluation (Table 2) showed high reliability under all conditions (ICCs ranged from 0.81 to 0.97). The reliability of the Sym score in the WBS evaluation varied depending on knee-flexion angles (Table 3); it was highly reliable while erect or during 30° flexion, and acceptably reliable at higher flexion angles. In the MCT evaluation, the Sym and RT scores were sufficiently reliable under all conditions (Table 4).

Table 2 Reliability of the unilateral stance in the instrumented treadmill test.

	Condition	ICC
MS (degree/s)	L-EO	0.81
	L-EC	0.95
	R-EO	0.97
	R-EC	0.85

ICC = intraclass correlation coefficient; L-EC = eyes closed standing on left leg; L-EO = eyes open standing on left leg; MS = mean of centre of gravity sway; R-EC = eyes closed standing on right leg; R-EO = eyes open standing on right leg.

Table 3 Reliability of the weight bearing square in the instrumented treadmill test.

	Knee flexion (degree)	ICC
Sym (%)	0	0.74
	30	0.93
	60	0.67
	90	0.69

ICC = intraclass correlation coefficient; Sym = weight Symmetry.

Table 4 Reliability of the Motor Control Test in the instrumented treadmill test.

	Conditions	ICC
Sym (%)	FM	0.85
	BM	0.8
	FL	0.84
	BL	0.72
RT (ms)	FM	0.83
	BM	0.87
	FL	0.78
	BL	0.75

BL = perturbation with a backward direction and a large distance; BM = perturbation with a backward direction and a medium distance; FL = perturbation with a forward direction and a large distance; FM = perturbation with a forward direction and a medium distance; ICC = intraclass correlation coefficient; RT = reaction time; Sym = weight symmetry.

Validity of the force-instrumented treadmill test compared with the EquiTest

Tables 5–8 show the validity of various measurements assessed in the force-instrumented treadmill test compared with the EquiTest. In the mCTSIB evaluation for overcoming unstable conditions, all participants obtained ESs averaging from about 76 to 92 and nearly perfect (100) SS in the treadmill test (Table 5). The correlation of the ESs and SSs using the force-instrumented treadmill with those of the EquiTest ranged from weak to moderate (Table 5). The MS scores in the US evaluations using the force-instrumented treadmill were mostly weakly correlated with those from the EquiTest (Table 6). The Sym values from the WBS evaluation showed weak to moderate correlation to those of the EquiTest (Table 7), while those of the MCT (Sym and RT measurements) showed slight to good correlation.

Discussion

As a preliminary study of feasibility, the present study assessed the reliability and validity of the force-instrumented treadmill for standing balance evaluations in healthy young adults. The results demonstrated that the force-instrumented treadmill was highly reliable in all balance evaluations. By contrast, the validity of the various tests tended to be varied among evaluations.

The generally high reliability results suggest that the force-instrumented treadmill has potential as a usable device for balance evaluations. The reliability of the measurements obtained with the force-instrumented treadmill was similar to those reported for the EquiTest (ICC $r = 0.67$–0.7) [32,33].

One of the reasons that it was possible to show this might be the similarity of the experimental procedures. Instruction and trial times per session were similar in the present treadmill study to those in previous EquiTest studies [32,33]. Especially, the trial times per session might contribute to minimizing the variation in anticipatory posture adjustments. Santos et al [34] showed that when perturbations first occur, an individual may not adjust to them, but after training three or more times, anticipatory posture adjustments are made enabling better performance.

Scores of the various tests obtained from the force-instrumented treadmill were different from those obtained from the EquiTest. These differences might have resulted from the confluence of various factors. One of the reasonable causes may be the difference in the stability of the two platforms. The force-instrumented treadmill used a quite stable platform, while the platform in the EquiTest is unstable, especially during the US test. To maintain balance on an unstable platform, more attention must be paid to maintaining stability, and compensatory movements must also be added in case of big sways or balance broken without prediction [9]. Other related research noted that a difference in the platform stability affects muscle activity

Table 5 Validity of the modified clinical test of sensory interaction on balance in the instrumented treadmill test with the EquiTest.

	Condition		EquiTest	Treadmill	Absolute error	Relative error	r	p
	Vision	Surface	(mean ± SD)	(mean ± SD)	(mean ± SD)			
ES	EO	Firm	95.36 ± 1.44	92.43 ± 2.1	−2.93 ± 2.65	−0.03	−0.10	0.78
	EC	Firm	93.33 ± 1.56	92.22 ± 2.14	−1.11 ± 2.22	−0.01	0.26	0.48
	EO	Foam	89.96 ± 3.38	85.56 ± 2.33	−4.42 ± 4.51	−0.08	−0.24	0.05
	EC	Foam	78.8 ± 4.53	76 ± 4.54	−2.8 ± 5.33	−0.09	0.44	0.20
SS	EO	Firm	99.74 ± 0.48	99.87 ± 0.07	0.13 ± 0.51	0	−0.41	0.24
	EC	Firm	99.04 ± 0.83	99.85 ± 0.06	0.81 ± 0.85	0.01	0.22	0.54
	EO	Foam	97.43 ± 1.45	99.78 ± 0.15	2.35 ± 1.49	0.02	0.06	0.87
	EC	Foam	94.37 ± 2.19	99.66 ± 0.15	5.29 ± 2.25	0.06	0.24	0.51

EC = eyes closed; EO = eyes open; ES = equilibrium score; Firm = firm surface; Foam = foam (unstable) surface; r = Spearman's rank correlation coefficient; SD = standard deviation; SS = strategy score.

Table 6 Validity of the unilateral stance in the instrumented treadmill test with the EquiTest.

	Condition	EquiTest (mean ± SD)	Treadmill (mean ± SD)	Absolute error (mean ± SD)	Relative error	*r*	*p*
MS (degree/s)	L-EO	0.62 ± 0.13	0.53 ± 0.05	0.08 ± 0.14	−0.03	−0.01	0.99
	L-EC	1.28 ± 0.36	0.54 ± 0.05	0.61 ± 0.51	−0.01	0.06	0.89
	R-EO	0.67 ± 0.16	0.55 ± 0.06	0.13 ± 0.17	−0.08	−0.02	0.95
	R-EC	1.45 ± 0.41	0.57 ± 0.06	0.88 ± 0.42	−0.09	−0.16	0.67

L-EC = eyes closed standing on left leg; L-EO = eyes open standing on left leg; MS = mean of centre of gravity sway; *r* = Spearman's rank correlation coefficient; R-EC = eyes closed standing on right leg; R-EO = eyes open standing on right leg; SD = standard deviation.

Table 7 Validity of the Weight Bearing Square in the treadmill test with the EquiTest.

	Knee flexion (degree)	EquiTest (mean ± SD)	Treadmill (mean ± SD)	Absolute error (mean ± SD)	Relative error	*r*	*p*
Sym (%)	0	97.39 ± 3.05	98.37 ± 5.3	−0.98 ± 4.45	0.01	−0.44	0.20
	30	101.05 ± 6.03	99.57 ± 6.39	1.48 ± 6.48	−0.01	0.55	0.10
	60	102.41 ± 5.79	100.87 ± 4.18	1.54 ± 2.70	−0.01	0.06	0.87
	90	99.52 ± 5.47	99.91 ± 3.83	−0.39 ± 3.2	0	0.44	0.20

r = Spearman's rank correlation coefficient; SD = standard deviation; Sym = weight symmetry.

Table 8 Validity of the Motor Control Test in the treadmill test with the EquiTest.

	Conditions	EquiTest (mean ± SD)	Treadmill (mean ± SD)	Absolute error (mean ± SD)	Relative error	*r*	*p*
Sym (%)	FM	93.95 ± 6.56	98.0 ± 5.38	−1.67 ± 4.44	0.02	0.50	0.14
	BM	95.09 ± 6.05	96.76 ± 5.53	−4.06 ± 4.90	0.05	0.82	0.004
	FL	97.03 ± 6.19	99.44 ± 5.38	−0.98 ± 4.25	0.01	0.73	0.02
	BL	95.93 ± 5.83	96.91 ± 5.61	−2.42 ± 5.44	0.03	0.61	0.06
RT (ms)	FM	134 ± 13.7	149 ± 15.6	−10 ± 22.9	0.08	0.85	0.002
	BM	126.5 ± 16.67	136.5 ± 30.6	−15 ± 11.8	0.11	0.67	0.03
	FL	129.5 ± 11.89	150.5 ± 11.41	−10 ± 14.7	0.08	0.63	0.05
	BL	124.5 ± 10.92	134.5 ± 19.36	−21 ± 11.9	0.17	0.62	0.06

BL = perturbation with a backward direction and a large distance; BM = perturbation with a backward direction and a medium distance; FL = perturbation with a forward direction and a large distance; FM = perturbation with a forward direction and a medium distance; *r* = Spearman's rank correlation coefficient; RT = reaction time; SD = standard deviation; Sym = weight symmetry.

[35]. In particular, on a stable platform, abductor muscles and pelvic muscles contracted to provide postural control. On the contrary, muscle activity of the hip adductor muscles increased on an unstable surface [35]. With a difference in the environment, difficulty of the tasks changed, possibly leading to low comparative validity. In addition, a factor in the low correlation coefficients might be a ceiling effect, which indicates low dispersion of data. Many of the participants in the present study obtained relatively high scores because these evaluations are mainly targeted to patients with dizziness or balance impairment [20,21], and our participants were healthy individuals. However, from a clinical standpoint, the small relative errors between the EquiTest and the force-instrumented treadmill in all the evaluations suggest that a force-instrumented treadmill is a beneficial tool for balance evaluation.

There are several limitations to this study. Firstly, the small number of participants may limit the strength of the conclusion. Secondly, we investigated only healthy individuals. The EquiTest focuses mainly on equilibrium disabilities. In this study, all the young healthy individuals chosen performed quite well in the balance evaluations, possibly demonstrating a ceiling effect. Further studies should be conducted in aging individuals or other persons with balance disorders after stroke or cervical myelopathy surgery.

Conclusion

The results demonstrated that all balance evaluations using a force-instrumented treadmill were strongly reliable, and some were highly valid. The treadmill can be set under the floor of the rehabilitation exercise rooms, solving the common spatial and temporal limitations with low costs.

Conflicts of interest

The authors declare no conflicts of interest associated with this study.

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Authors' contributions

Yuntao Zhou, Kensuke Oono and Takuma Ii participated in the study conception and design, data collection, data analysis, data interpretation, writing of manuscript and revising of manuscript. Izumi Kondo, Masahiko Mukaino and Toshio Teranishi participated in the study conception and design, data interpretation, writing of manuscript and revising of manuscript. Yoshikiyo Kanada and Eiichi Saitoh participated in the study conception and design, and writing of manuscript. Shigeo Tanabe and Soichiro Koyama participated in the study conception and design, writing of manuscript and revising of manuscript, and provided technical support.

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