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Original Article

Three-dimensional Evaluation of Abnormal Gait in Patients with Hip Osteoarthritis

Daisuke Homma[a,b]*, Izumi Minato[c], Norio Imai[d], Dai Miyasaka[e], Yoshinori Sakai[f], Yoji Horigome[a], Hayato Suzuki[a], Hayato Shimada[g], Yoichiro Dohmae[e], and Naoto Endo[a]

Divisions of [a]Orthopedic Surgery, [d]Comprehensive Geriatrics in Community, Niigata University Graduate School of Medical and Dental Sciences, Niigata 951-8510, Japan, Divisions of [b]Rehabilitation, [e]Orthopedic Surgery, Niigata Bandai Hospital, Niigata 950-8584, Japan, [c]Division of Orthopedic Surgery, Niigata Rinko Hospital, Niigata 950-0051, Japan, [f]Division of Orthopedic Surgery, Niigata General Hospital, Niigata 950-1197, Japan, [g]Division of Orthopedic Surgery, Mito Saiseikai General Hospital, Mito City, Ibaraki 311-4198, Japan

Indexes for objectively evaluating abnormal gait in hip osteoarthritis (OA) patients and determining effective interventions are unclear. We analyzed the abnormal gait of hip OA patients by focusing on movements of the trunk and pelvis to establish an effective evaluation index for each direction of motion. We studied 28 patients with secondary hip OA due to developmental dysplasia of the hip and 16 controls. The trunk and pelvic movements during gait were measured in the medial-lateral (x), vertical (y), and back-and-forth (z) directions by a triaxial angular accelerometer. Gait speed, steps, step length, muscle strength, range of motion, and timed up-and-go (TUG) test performance were measured. We determined the correlations between physical function and the index of abnormal gait in the hip OA patients. Movements other than trunk and pelvic motions in the y-direction indicated abnormal gait in the patients. Significant correlations were found between abnormal gait and range of motions (extension, internal rotation), TUG score, stride length, and steps. The TUG test, stride length and steps were important for evaluating abnormal gait in hip OA patients. Individual interventions for each movement direction are required.

Key words: hip osteoarthritis, three-dimensional gait analysis, abnormal gait, timed up and go test, range of motion

Hip osteoarthritis (OA) is a chronic and progressive degenerative disease. In addition to deformation of the hip joint, patients with hip OA may experience restricted range of motion (RoM), muscle weakness, pain during loading, leg length difference, and abnormal gait [1-5]. Patients with hip OA have an abnormal gait because of hip deformity, which is easily recognized based on increased trunk and pelvic disturbances.

In 2016, Tateuchi *et al.* [6] investigated stress in the hip joint and changes in the radiographs of hip OA patients and found that the radiographic changes and the cumulative load of the hip joint were related. They reported that abnormal gait and stress of the hip joint were related. Abnormal gait in hip OA has also been reported to cause a decrease in walking efficiency [7]. These findings suggest that it is particularly important for hip OA patients to improve their gait.

To improve the abnormal gait in hip OA patients,

Received November 5, 2019; accepted May 25, 2020.
*Corresponding author. Phone : +81-25-244-4700; Fax : +81-25-247-6216
E-mail : daisukehomma24@gmail.com (D. Homma)

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objective assessments of abnormal gait and effective interventions are required. Previous studies have used motion capture and wearable sensors on the trunk and pelvis to objectively evaluate abnormal gait [2,8,9]. It is difficult to obtain biomechanical gait information as a numerical value in clinical practice. Wearable sensors are devices that can easily evaluate three-dimensional gait; they can measure acceleration, angular velocity, and magnetism and have been used for gait analyses. Wearable sensors can be quickly mounted on patients, and the gait analysis can be conducted without burdening the patient [10]. With the determination of the relationship between an abnormal gait evaluated by a wearable sensor and an evaluation index that can be easily appraised in clinical settings, it would be possible to further verify the effectiveness of the evaluation index of abnormal gaits in clinical settings. We believe that abnormal gaits can be effectively improved by clarifying the physical functions related to abnormal gaits in hip OA patients.

Therefore, we conducted the present study to analyze abnormal gaits in hip OA patients by focusing on trunk and pelvic movements with the use of wearable sensors, toward the goal of establishing effective evaluation indexes for each direction of motion and physical functions for improving abnormal gaits.

Subjects and Methods

Ethical considerations. This study was conducted with the approval of the Ethics Committee of Niigata Bandai Hospital (approval no. 54). The study subjects were informed of all of the study's aims and methods, and written consent was obtained from each study before they participated in the study.

Subjects. A total of 65 patients with hip OA were analyzed during the evaluation period from June 2017 to December 2018. All of the patients were able to walk without using a cane (or similar walking aid) and had no cognitive impairment. The exclusion criteria for the patients were as follows: (1) pain in any joint other than the joint scheduled for total hip arthroplasty (n = 26), (2) advanced or end-stage OA in the contralateral hip joint, as determined according to the Japanese Orthopaedic Association (JOA) criteria [11] (n = 5), and (3) history of hip disease other than hip OA due to developmental dysplasia of the hip (*e.g.*, osteotomy at infancy or primary hip OA) (n = 6). After exclusion, a total of 28 patients were included for the final analysis. These 28 patients had been diagnosed with unilateral secondary hip OA due to developmental dysplasia of the hip, and each patient's condition was evaluated using the JOA criteria [11]. The hip joint function of each hip OA patient was evaluated using the JOA hip score.

Abnormal gait in the hip OA patients was evaluated by focusing on the trunk and pelvis and by evaluating the relationship between physical function and movement. To clarify the characteristics of the abnormal gaits of the patients, a control group was established, and trunk and pelvis movements were compared between the control group and the patient group. Individuals were recruited to the control group by the medical staff at Niigata Bandai Hospital, Rinko Hospital; the group consisted of 16 healthy subjects without orthopedic diseases and/or any other diseases of the lower limbs.

Measurements. The root mean square (RMS) acceleration of the trunk and pelvic motion during gait was calculated as an indicator of abnormal gait in the hip OA patients. The RMS acceleration was analyzed from acceleration waveforms measured by a body fixed sensor (BFS) that measured the wearer's trunk and pelvic movements. We measured and analyzed each subject's stride length, gait speed, steps, and pain during gait. Physical function was evaluated from the following parameters: hip joint muscular strength, range of motion (RoM), the timed up-and-go (TUG) test results, and the spinomalleolar distance (SMD).

1. Gait analysis

The following equipment was used to measure the RMS of the subject's trunk and pelvis during his or her gait: a triaxial angular accelerometer (MVP-RF8-HC-500, Micro Stone, Nagano, Japan), a Bluetooth USB adapter (Parani-UD 100, InterSolution Marketing, Tokyo), measurement software (MVP-RF-8-S, Micro Stone), a digital camera (EX-ZR300, Casio, Tokyo), and a stopwatch (TCE-2056-WT, Crepha, Tokyo). Data were wirelessly transmitted to a personal computer and analyzed using a sensor data analyzer (ATR-Promotions, Kyoto, Japan); Microsoft Excel was then used for further analysis.

The measurement range of the BFS acceleration sensor was ± 20 m/sec^2. The triaxial angular accelerometer used in this study was $4.5 \times 4.5 \times 1.8$ cm in size and weighed 60 g. The response frequency was 70 Hz. Two BFSs were used. The measurements were obtained as follows. First, the triaxial angular accelerometer was activated 15 min before measurement to eliminate room-temperature effects and ensure accurate measurements. The BFS was placed horizontally with a vertical y-axis and was calibrated. The BFS was then positioned at the posterior superior iliac spine, while another BFS was positioned at the level of the subject's spinal process of the 7th cervical vertebra [12] (Fig. 1). The BFS can measure acceleration in the medial-lateral (x), vertical (y), and back-and-forth (z) directions. For the evaluation of the steps, a digital camera was used to capture videos during each trial. The subject walked on a 16-m walkway that included a 4-m straight line, at a comfortable and normal speed. The accelerations of the trunk and pelvis were measured using the BFS; the step count was determined using a video camera, and the total time was recorded using a stopwatch.

The offset between static position and gait were identified as the data obtained during the subject's stationary standing for 1 sec before walking and was removed by the sensor data analyzer. Then, along with a fourth-order Butterworth filter, a low-pass filter of 8 Hz was used [13]. After filtering, heel contact was identified from the acceleration waveform in the z-direction of the pelvis [14], and a stable 5 gait cycle was set as an analysis section. The acceleration waveform in the analysis section was calculated using the RMS function in Microsoft Excel with the following integral:

$$Xrms = \sqrt{\frac{1}{T}\int_{0}^{T} x(t)^2 dt}$$

where T is the period of the periodic signal x (t).

The RMS has been used to evaluate abnormal gait [15, 16]. The RMS can be used as an index of abnormal gait to identify movement during gait; if the RMS value is large, it can be interpreted that there is a large amount of movement [17]. As the RMS is influenced by gait speed, we divided the RMS by the square of the gait speed, and the influence of the walking speed was excluded [17]. The stride length and walking speed were also calculated. Because the stride length may differ depending on the subject's physique, the stride length was divided by the subject's height. The gait speed was calculated by dividing the gait distance by the gait time.

Fig. 1 Wearable sensor attachment site. This sensor is a triaxial angular accelerometer. The application site was on the 7th cervical vertebra, and the acceleration of the trunk during gait was measured. A triaxial angular accelerometer attached to the midpoint of the posterior superior iliac crest on both sides measured the acceleration of the pelvis during the wearer's gait.

2. RoM and lower-limb muscle strength

The RoM and the muscular strength around the hip joint were calculated in all directions of motion, including flexion, extension, abduction, external rotation and internal rotation. Muscle strength was evaluated as described by Thorborg *et al.* [18]. Coarse muscle strength was evaluated using a manual muscle strength meter, which involves the performance of maximal voluntary isometric contraction twice, for 5 sec each, in all directions (Fig. 2: hip flexion, extension, abduction, external rotation and internal rotation). The peak value was used as the representative value. The RoM of the hip joint in all directions was measured by a goniometer.

3. TUG test

The TUG test, as devised by Podsiadlo and Richardson [19], was used to assess ambulatory ability. The subject was instructed to rise from a standard chair, walk to a point on the floor 3 m away from the chair, return to the chair and sit down again as fast as possible; the amount of time it took for the subject to complete the task was recorded. The TUG test is a general evaluation method for evaluating gait ability and has been used in many previous studies [20, 21].

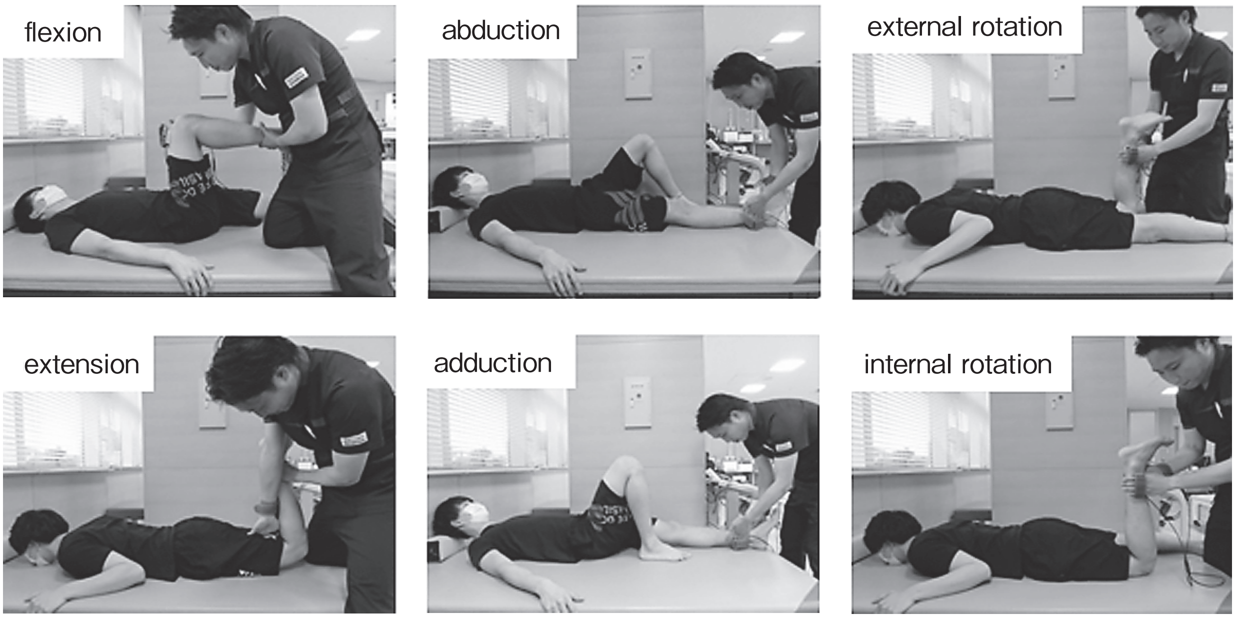

Fig. 2 Measurement positions for muscle strength. The muscle strength was measured with the subject in the supine position and prone position so as not to be a burden on the subject.

4. Leg length difference

Measurements of leg length were taken with the subject in the supine position. We used the SMD to evaluate leg length differences. The SMD measured as the distance from the superior anterior iliac crest to the intima. The difference between the measured left and right leg lengths was taken as the leg length difference.

Statistical analyses. All statistical analyses were performed using SPSS software (ver. 21, IBM Corp., Armonk, NY, USA). All data are reported as the median and interquartile range (25%, 75%). The differences of trunk and pelvis movements between the hip OA patients and healthy controls during gait were analyzed using the Mann-Whitney *U*-test. To determine the relationship between the parameters of the disabled leg and the opposite leg, we used the Wilcoxon signed rank test. In the analyses of the motion of the hip OA patients during their gaits, Spearman's rank-order correlation (non-normal distribution) was used to evaluate the correlation between trunk and pelvic movements with regard to the direction and physical function. The correlation was examined in terms of body structure. Probability p-values < 0.05 were considered significant.

Results

There were significant differences in age and height between the OA group ($n = 28$) and control group ($n = 16$) (Table 1). The OA group was significantly older and shorter in height than the controls. The trunk and pelvic motions were greater for the hip OA patients compared to the controls, with significant differences in trunk motion and pelvic motion in the x- and z-directions (Table 2). In the hip OA patients, all muscle strength and RoM measurements were significantly smaller for the unilateral side of the hip than for the contralateral side (Table 3). With respect to the relationships among muscle strength, sway during gait, and gait parameters, no variables were significantly related (Table 4).

The relationship between the RoM of the hip joint, the sway during gait, and gait parameters were significantly related to the motion direction of the extension (trunk: x, step length), abduction (step length, steps), and internal rotation (pelvis: z) (Table 5). The TUG test results, stride length and steps were significantly correlated with trunk and pelvic motions in all directions (Table 6).

Table 1 Patient demographics

	Hip OA patients		Healthy controls	*p* value
Age (years)	61.5 [58.7, 66.5]		30.0 [25.7, 44.2]	<0.01*
Height (cm)	157.6 [152.3, 162.1]		165.0 [160.4, 174.2]	<0.01*
Weight (kg)	53.3 [47.9, 63.2]		55.5 [51.3, 61.1]	0.981
Radiographic stage	OA side	Contralateral side		
Normal	0	13		
Pre-arthritic stage	1	8		
Early stage	1	7		
Advanced stage	11	0		
End stage	15	0		
JOA hip score	46.0 [41.7, 57.2]	93.0 [90.7, 96.0]		
Leg length discrepancy (cm)	1.0 [0, 1.25]			

*$p<0.05$. JOA, Japan Orthopaedic Association; OA, osteoarthritis. The patients had unilateral and secondary osteoarthritis of the hip, and no pain other than the OA side.

Table 2 Differences between trunk and pelvis movements during gait in the hip OA patient and control groups

	Direction	Hip OA patients	Healthy controls	*p* value
Trunk movements (RMS)	x	1.4 [0.8, 2.1]	0.6 [0.5, 0.7]	<0.01*
	y	1.5 [1.3, 1.9]	1.4 [1.3, 1.6]	0.242
	z	1.2 [1.0, 1.4]	0.8 [0.7, 0.9]	<0.01*
Pelvic movements (RMS)	x	1.5 [1.2, 1.8]	0.7 [0.6, 0.9]	<0.01*
	y	1.7 [1.4, 2.2]	1.4 [1.2, 1.8]	0.067
	z	1.5 [1.0, 2.0]	1.1 [1.1, 1.2]	<0.01*

*$p<0.05$. RMS, root mean square. Significant differences were found between hip OA patients and controls during gait, except in the trunk and pelvis in the y-direction. The difference was large in the patients, suggesting that hip OA patients show much movements during their gait.

Table 3 Differences in lower extremity function of the OA side and contralateral side

	Movement	OA side	Contralateral side	*p* value
Muscle power (kgf)	flexion	13.8 [10.7, 16.1]	15.4 [12.3, 19.9]	<0.01*
	extension	14.3 [12.6, 16.8]	17.2 [14.4, 21.3]	<0.01*
	abduction	9.1 [6.8, 9.9]	11.3 [9.4, 12.5]	<0.01*
	adduction	9.7 [7.3, 10.5]	11.8 [9.2, 13.2]	<0.01*
	external rotation	9.1 [6.3, 12.1]	11.8 [8.5, 13.2]	<0.01*
	internal rotation	8.6 [1.0, 10.8]	11.5 [8.4, 13.2]	<0.01*
Range of motion (°)	flexion	105.0 [93.7, 120]	120 [110.0, 126.2]	<0.01*
	extension	5.0 [5.0, 10.0]	15.0 [10.0, 15.0]	<0.01*
	abduction	20.0 [13.7, 30.0]	40.0 [33.7, 40.0]	<0.01*
	adduction	17.5 [10.0, 20.0]	20.0 [20.0, 20.0]	<0.01*
	external rotation	32.5 [20.0, 40.0]	45.0 [30.0, 45.0]	<0.01*
	internal rotation	20.0 [13.7, 25.0]	35.0 [28.7, 45.0]	<0.01*

*$p<0.05$. The OA side showed a significantly smaller value than between the OA side and contralateral side. The OA side exhibited muscle weakness and a limited RoM.

Discussion

Gait analyses are important for OA patients with abnormal gait. A gait analysis using motion capture allows for a detailed analysis, but the use of motion capture technology requires a laboratory equipped with expensive equipment such as a floor reaction force meter, and clinical settings usually are not capable of

Table 4 Relationship between trunk and pelvis movements during gait and related functions

	Direction of movements / OA side physical function		Trunk x	Trunk y	Trunk z	Pelvis x	Pelvis y	Pelvis z	Step length (% height)	Steps
Muscle power	flexion	r	0.019	0.018	0.105	0.121	0.009	−0.027	−0.096	0.034
		p value	0.920	0.925	0.591	0.537	0.961	0.888	0.623	0.862
	extension	r	−0.113	−0.104	−0.100	−0.071	−0.057	−0.208	−0.03	−0.133
		p value	0.569	0.597	0.611	0.719	0.769	0.287	0.879	0.499
	abduction	r	−0.117	−0.024	−0.137	−0.099	−0.101	−0.144	−0.002	−0.082
		p value	0.551	0.900	0.483	0.612	0.608	0.463	0.991	0.675
	adduction	r	−0.159	−0.090	−0.188	−0.089	−0.148	−0.197	0.116	−0.160
		p value	0.416	0.464	0.335	0.650	0.451	0.314	0.554	0.413
	external rotation	r	−0.293	−0.345	−0.305	−0.309	−0.325	−0.468	0.069	−0.226
		p value	0.129	0.071	0.113	0.109	0.091	0.011	0.723	0.245
	internal rotation	r	−0.235	−0.157	−0.205	−0.094	−0.173	−0.293	0.054	−0.138
		p value	0.227	0.422	0.294	0.633	0.377	0.129	0.784	0.481

To prevent multiple comparisons, the significance level was set to $^{*}p<0.006$ using the Bonferroni correction. With regard to the relationship between muscle strength, sway during gait, and gait parameters, no items were significantly related.

Table 5 Relationships among trunk and pelvis movements during gait, the RoM, and gait parameters

	Direction of movements / OA side physical function		Trunk x	Trunk y	Trunk z	Pelvis x	Pelvis y	Pelvis z	Step length (% height)	Steps
Range of motion	flexion	r	−0.457	−0.421	−0.246	−0.346	−0.320	−0.388	0.402	−0.425
		p value	0.014	0.025	0.205	0.070	0.096	0.041	0.033	0.023
	extension	r	−0.575	−0.425	−0.375	−0.226	−0.318	−0.304	0.541	−0.477
		p value	0.001*	0.024	0.048	0.247	0.098	0.114	0.002*	0.010
	abduction	r	−0.437	−0.497	−0.450	−0.328	−0.289	−0.418	0.570	−0.618
		p value	0.019	0.007	0.028	0.087	0.135	0.027	0.001*	<0.001*
	adduction	r	−0.235	−0.175	−0.011	−0.097	−0.102	−0.137	0.192	−0.245
		p value	0.228	0.373	0.952	0.623	0.601	0.483	0.325	0.207
	external rotation	r	−0.307	−0.237	−0.390	−0.293	−0.272	−0.156	0.355	−0.391
		p value	0.112	0.224	0.040	0.130	0.160	0.427	0.063	0.039
	internal rotation	r	−0.410	−0.332	−0.331	−0.253	−0.392	−0.526	0.258	−0.246
		p value	0.030	0.085	0.084	0.193	0.039	0.004*	0.184	0.205
	leg length discrepancy	r	−0.105	−0.032	−0.222	−0.147	−0.173	−0.170	−0.033	−0.102
		p value	0.594	0.870	0.256	0.456	0.378	0.387	0.868	0.605

To prevent multiple comparisons, the significance level was set to $^{*}p<0.006$ using the Bonferroni correction. The relationship between the RoM of the hip joint, the motion during gait, and gait parameters were significantly related to the motion direction of the extension (trunk: x, step length), abduction (step length, steps), and internal rotation (pelvis: z).

such motion capture assessments [22-24]. We thus analyzed the subjects' gait by using wearable sensors in this study. Wearable sensors can be quickly mounted on a patient, and the gait can be analyzed without burdening the patient [11].

Our results indicate that the abnormal gait in the hip OA patients was large in the x-direction (anterior/posterior) and z-direction (medio/lateral) but not in the y-direction (up and down). For the assessment of an abnormal gait, objective evaluations of movements in the x- and z-directions are necessary. The results of our present analyses suggest that abnormal gaits in hip OA

Table 6 Relationship between trunk, pelvis movements during gait, Timed Up and Go test results, step length and steps

	Direction of movements		Trunk			Pelvis		
	OA side physical function		x	y	z	x	y	z
Gait parameter	pain (VAS: in gait)	r	0.272	0.225	0.246	0.267	0.228	0.346
	5.5 [3.2, 6.8]	*p* value	0.161	0.249	0.206	0.170	0.244	0.071
	Timed Up and Go (sec)	r	0.790	0.643	0.643	0.501	0.502	0.631
	7.7 [6.5, 10.0]	*p* value	<0.001*	<0.001*	<0.001*	0.007*	0.007*	<0.001*
	step length (% height)	r	−0.848	−0.800	−0.755	−0.689	−0.709	−0.745
	33.0 [29.3, 34.9]	*p* value	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
	steps	r	0.856	0.857	0.741	0.789	0.750	0.838
	30.5 [28.7, 35.5]	*p* value	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*

VAS, visual analog scale. To prevent multiple comparisons, the significance level was set to $*p<0.008$ using the Bonferroni correction. The stride length (% height) had a significant negative correlation with all movements of the trunk and pelvis. The TUG test result and steps had a significant positive correlation with all trunk and pelvic movements.

patients may not be evaluated adequately by a frontal evaluation alone. Hip OA patients show Trendelenburg and Duchenne gaits, in which trunk and pelvis motions are identified on the frontal plane. For evaluations of abnormal gait in hip OA patients, several researchers reported performing a gait analysis in only one direction [10, 23]. It is highly likely that a three-dimensional evaluation is necessary for more accurate analyses.

In our study, no significant difference in the y- (up and down) direction between the hip OA patients and control group were noted (Table 2). In our hypothesis, we speculated that the leg length difference of hip OA patients was related to the movements in the y-direction. However, there was no significant correlation between the leg length difference and movement in the y-direction (Table 5). An increase in motion in the y-direction during gait is likely to increase the vertical movement of the center of gravity, and it is expected that a decrease in gait efficiency will occur. We thus speculate that motion in the x- and z-directions were compensated, and no significant difference occurred in the y-direction. However, this possibility must be examined further in additional investigations.

The TUG result, step length and steps were each significantly correlated with all of the trunk and pelvic movements. This suggests that hip OA patients who can perform the TUG test quickly have less sway during gait. It was reported that elderly people who perform the TUG test quickly have good dynamic balance [20]. In our present investigation, the patients who were quick during the TUG test were considered to have excellent balance ability and physical function. The TUG test result was thus suggested to be an effective index of abnormal gait.

Regarding the step length and steps, we observed that the hip OA patients with a larger stride and fewer steps exhibited minimal movements of the trunk and pelvis during their gait. This may have been influenced by the RoM of the patients. A decrease in hip-joint RoM results in a shorter stride length, and a compensatory movement causes an increase in motion instability. In our hip OA patients, the RoM of the side of the hip with OA was also significantly reduced compared to that of the opposite side (Table 3). The extension and abduction RoMs were found to be significantly related to gait parameters (Table 5). For this reason, we believe that a reduction in the stride length and an increase in the steps reflect functional impairment of a hip with OA. Our findings suggest that the TUG test result, step length and steps may be useful indicators of abnormal gait in hip OA patients.

The extension and internal rotation RoM values were significantly associated with abnormal gait and gait parameters (Table 5). The results of this study indicate that the RoM of the hip joint was related to movements during gait, suggesting that this RoM may be useful as the basis of an intervention to improve abnormal gait. The restricted RoM of the hip likely makes it difficult to perform normal stance and swing and results in compensatory motions. Considering the structure of the hip joint and the background of hip OA, the occurrence of compensatory movement may appear as swaying of the trunk and pelvis. We propose that the improvement of the hip joint's RoM can consequently improve an abnormal gait.

Muscle strength was reduced on the patients' OA side but was not significantly correlated with their trunk or pelvis movements during gait. We measured the maximum voluntary isometric contraction by using a manual muscle meter in this study, whereas earlier studies evaluated muscle dynamics in real time by using electromyography [25,26]. Since the present study could not assess muscle dynamics during gait, many muscles did not show a significant correlation with abnormal gait.

There are some study limitations that should be addressed. First, the control group was significantly younger and was not age- or gender-matched. Second, the muscular strength of the patients' impaired limb was measured as the coarse muscle strength; the measurement of muscle dynamics during gait in real-time could not be performed. Moreover, the method of correcting acceleration data was not based on the data of each subject but rather was based on previous studies. Additionally, because we set strict exclusion criteria for the subjects, our sample sizes were insufficient. Prospective studies should include a larger number of patients and control subjects from multiple centers and should have an age- and gender-matched control group for better comparison.

In this study, three-dimensional evaluations of trunk and pelvic motions of hip OA patients were used to determine effective evaluation indexes and physical function for each direction of movement. Improving an abnormal gait is important for physical therapy, because an abnormal gait in hip OA patients is associated with an increase in mechanical stress, increased deformation of the hip joint, and deterioration in the patients' quality of life [27]. The results of our analyses demonstrated that the TUG test result, stride length, and steps are associated with abnormal gait and may each be an effective index in clinical practice. We suspect that focusing on the extension, abduction, and internal rotation movement range during intervention is likely to be effective for improving an abnormal gait. Further studies are required to evaluate the effectiveness of such intervention strategies. The results of this study can be applied in clinical practice and will be important for evaluating and improving abnormal gaits in hip OA patients.

In conclusion, the OA hip was found to sway more in all directions of movement, except in the y-direction of the trunk and pelvis. It is necessary to evaluate an abnormal gait in three dimensions. Evaluations of the TUG test result, steps, and stride length were identified as simple indices for the assessment of abnormal gaits. The determination of the extension, abduction, and internal rotation movement ranges of hip OA patients are particularly likely to be effective for improving their abnormal gaits.

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