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Clinical Feasibility of a Markerless Gait Analysis System

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Background: The gait analysis method that has been used in clinical practice to date is an optical tracking system (OTS) using a marker, but a markerless gait analysis (MGA) system is being developed because of the expensive cost and complicated examination of the OTS. To apply this MGA clinically, a comparative study of the MGA and OTS methods is necessary. The purpose of this study was to evaluate the compatibility between the OTS and the MGA methods and to evaluate the usefulness of the MGA system in actual clinical settings.

Methods: From March 2021 to August 2021, 14 patients underwent gait analysis using the OTS and MGA system, and the spatiotemporal parameters and kinematic results obtained by the 2 methods were compared. To evaluate the practicality of the MGA system in an actual clinical setting, MGA was performed on 14 symptomatic children with idiopathic toe walking, who had been treated with a corrective cast, and the pre-cast and post-cast results were compared. For the OTS, the Motion Analysis Eagle system was used, and for MGA, DH Walk was used.

Results: The spatiotemporal parameters showed no significant difference between the OTS and MGA system. The joint angle graphs of the kinematics along the sagittal plane showed similar shapes as a whole, with particularly high correlations in the hip and knee (pelvis: 29.4%, hip joint: 96.7%, knee joint: 94.9%, and ankle joint: 68.5%). A quantified comparison using the CORrelation and Analysis (CORA) score also showed high similarity between the 2 methods. The MGA results of pre-cast application and post-cast removal for children with idiopathic toe walking showed a statistically significant improvement in ankle dorsiflexion after treatment ($p < 0.001$).

Conclusions: MGA showed a good correlation with the conventional OTS in terms of spatiotemporal parameters and kinematics. We demonstrated that ankle sagittal kinematics improved after treatment by corrective cast in children with idiopathic toe walking using the MGA method. Thus, after the improvement of a few limitations, the MGA system may soon be able to be clinically applied.

Keywords: *Gait analysis, Pathologic gait, Optical tracking system, Markerless gait analysis*

Walking is the act of moving the human body forward by means of continuous movement of joints and muscles and has a relatively regular pattern.[1)] Many patients with neuromuscular diseases show various deviated gait patterns according to the pathology. It is very important to evaluate and treat these patients by analyzing the pathologic gait qualitatively and quantitatively.[2)] In general, using computer-assisted 3-dimensional (3D) gait analysis, it is possible to obtain spatiotemporal parameters, kinematics, kinetics data, electromyography (EMG) parameters, and energy consumption during walking.[3,4)]

To date, the most common method for 3D gait analysis is an optical tracking system (OTS). In the OTS

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method, raw data are obtained with passive reflective markers on the body and infrared cameras, and kinematic data are obtained using various software and computers for post-processing of raw data.[5,6] However, using the OTS method, patients are required to have often expensive and cumbersome markers and EMG surface leads attached to designated body parts, all of which are required for data capturing and post-processing.

Recently, thanks to the development of a time-of-flight (ToF) camera using 3D depth-sensing technology (e.g., KINECT) and automatic skeleton tracking algorithms, markerless gait analysis (MGA) methods have been introduced. To date, MGA methods have been developed to evaluate treadmill walking using these technologies.[7,8] This MGA method enables gait analysis even in compact spaces without the need for markers; thus, the entire gait analysis process is simplified and is more cost- and time-effective than the OTS method.

In South Korea, several MGA systems have been developed to the stage of commercialization. However, for MGA to be commercialized, further research on its compatibility with the existing OTS methods and on its accuracy and feasibility for medical use is necessary. Therefore, the purpose of this study was (1) to evaluate the compatibility between the OTS and MGA methods by comparing the gait data (spatiotemporal parameters and kinematic results) obtained by the 2 methods and (2) to evaluate the usefulness of the MGA system at this stage in an actual clinical setting.[9]

METHODS

This study was exempt from Institutional Review Board approval due to its retrospective nature and the requirement for informed patient consent was waived.

Gait Analysis

For the OTS in this study, passive reflection markers (Helen Hayes marker set, Reflective soft marker, Motion Analysis) and 6 charge-coupled device cameras (Eagle system, Motion Analysis) were used. Cortex version 7.2 (Motion Analysis) was used for basic motion capture, while OrthoTrak OT664 (Motion Analysis) and SIMM (Software for Interactive Musculoskeletal Modeling, Motion Analysis) were used for post-processing of gait data. A motion was captured 60 times per second.

DH Walk, which was newly developed and is in the pre-commercial stage, was used as the MGA system in this study. This system consists of a ToF camera (Azure Kinect, Microsoft), a treadmill for a walkway, and software developed by the Department of Mechanical Engineering at Hongik University.

The ToF system measures the time it takes for the infrared light to reach the object from the source and then travel back to the sensor. From this time delay (ToF), the depth (d) of the object is computed. Joint data obtained using Azure Kinect were post-processed with MATLAB (MathWorks) engineering software (Fig. 1).

In this study, a 3D ToF camera was installed on the front of the treadmill. The slope of the treadmill was set to 0° to simulate walking on flat ground. The length of the belt was set to be longer than 1.15 m, which is the average stride length of Korean adults, for comfortable walking during gait analysis. For the OTS in this study, in the gait lab at a distance of approximately 7 m, the average of walking 3 to 5 times in the second half was adopted and used in this study after 10 to 15 trials. All tests were conducted with volunteers who agreed to undergo the gait analysis. Patients for whom testing on a treadmill was considered dangerous were excluded from the examination. For example, children with cerebral palsy with Gross Motor Function Classification System (GMFCS) levels 3, 4, and 5 were excluded.

The gait analysis using the OTS was performed for ground walking, and MGA was performed for treadmill walking. For the treadmill gait analysis, the patient first walked on the treadmill to adapt to the treadmill and to determine a comfortable walking speed. The test was conducted at this speed. The average adjustment time was about 5 minutes for both ground walking and treadmill walking. The gait analysis on the ground was conducted at a comfortable walking speed for the patients. This prospective study included 2 studies: study 1 was designed to determine the compatibility of the MGA, and study 2 was designed to determine the clinical usability of MGA systems developed to date.

Study 1

From March to August 2021, the OTS and MGA system were simultaneously used to evaluate 14 patients for Study 1. As a 2-sided test with the significance level set to 0.05 and verification strength (power) around 0.8, 26 cases were required in each group, but the study had 28 cases (14 patients with both legs), which is more than 26 cases. The study group included various pathologies, such as knee arthritis in 3 patients, mild cerebral palsy in 2 patients, idiopathic toe walking (ITW) in 3 patients, in-toeing gait in 2 patients, out-toeing gait in 2 patients, and normal gait in 2 patients. There were 8 males and 6 females, with an average height of 160.4 cm, an average weight of 63.2 kg, and

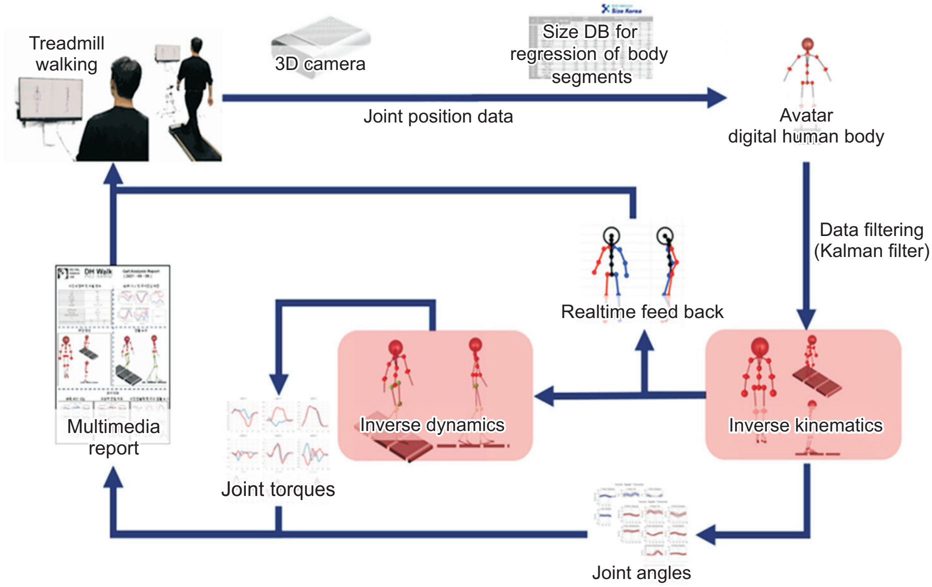

Fig. 1. Flow diagram of DH Walk. The MGA system (DH Walk) consists of a ToF camera, treadmill, and PC. The ToF camera used in this study was Microsoft's Azur Kinect, which was set to capture 30 frames per second (30 Hz), with an operating range of 0.25–2.88 m (WFOV). The software for data processing included Body Tracking SDK (Microsoft), Kalman filter, MATLAB (MathWorks, MA, USA), and SimulationX (ESI ITI, France). DB: database.

Table 1. Patient Demographic Data

Patient group	Number of patients	Sex (male : female)	Age (yr)	Height (cm)	Weight (kg)	BMI (kg/m^2)
Normal	2	1 : 1	40	173.1	70.7	23.4
Out-toeing gait	2	1 : 1	10	144.0	49.2	23.6
Knee arthritis	3	1 : 2	56	172.3	76.5	25.7
Mild cerebral palsy	2	2 : 0	23	172.2	70.3	23.7
Idiopathic toe walking	3	2 : 1	11	149.6	57.2	25.7
In-toeing gait	2	1 : 1	13	150.6	52.0	23.1

BMI: body mass index.

an average body mass index of 24.4 kg/m^2 (Table 1).

Temporal parameters and kinematic data were obtained by the OTS and MGA methods, and the results of both tests were compared. Temporal parameters including velocity, cadence, stride length, stance, swing (% cycle), and double support (% cycle) obtained from the 2 tests were compared. The kinematic data obtained from each joint were compared and analyzed for the similarity in the maximum value, minimum value, and range of motion in the stance and swing phases, and the patterns of the graphs.

To evaluate the similarity between the OTS and MGA methods, the kinematic graphs obtained from each system were quantitatively compared using the CORrelation and Analysis (CORA) score. The CORA score determines how closely 2 curves match by comparing their phase, slope, and magnitude. A score of 0 indicates no correlation, and a score of 1 represents a perfect match between 2 kinematic graph curves obtained from each system.

The corridor rating calculates the deviation between both curves with the help of user-defined or automatically generated corridors. The cross-correlation rating analyzes specific curve characteristics, such as the phase shift, size, and shape of the signals. In this study, data similarity was judged by a cross-correlation score. ISO/TR 9790 was used as a criterion to judge the meaning of the CORA score (ISO, 1999) to evaluate the Biofidelity of an experimental human body model such as a dummy or a mathematical model, and the overall reliability level was divided into 5 grades. In this paper, this grade was applied to the CORA score to evaluate the similarity of joint angles (Table 2). To evaluate the convenience of the test, the time taken for each gait analysis was compared.

Study 2

To determine the usefulness of the MGA system at this stage in an actual clinical setting, MGA was performed on 14 children with ITW who had been treated with a corrective cast (Table 3). After consent for the cast treatment and study enrollment was obtained, a short leg cast was applied by a single pediatric orthopedist (HYK) in all patients in the ITW group. After padding with a stockinette and cotton rolls, a fiberglass cast (3M Scotchcast Plus Casting Tape) was applied below the knee over both limbs with maximum dorsiflexion of the ankle, 90° knee flexion, and slight inversion of the foot with arch molding. The children were encouraged to stand and walk as much as possible. After 7 days, the patient visited the outpatient clinic to have the degree of ankle dorsiflexion evaluated, and if the degree of dorsiflexion was less than 5°, another corrective cast was applied for an additional 7 days. In the case of ITW children, the test could be performed during such a short outpatient follow-up period. In addition, patients with walking of GMFCS levels 1 and 2 were selected to measure MGA because there were no major problems with treadmill walking.

MGA was performed on the day the plaster bandage was applied and on the day the cast was removed. MGA was performed by a single skilled physiotherapist (HCL) with a single machine. The kinematic results obtained by MGA were analyzed by dividing the results into 4 areas including 3 ankle rockers and the swing phase. Furthermore, ankle joint angles before and after corrective cast treatment were measured using MGA and a protractor.

Table 2. CORA Score Grade

Scale	CORA score
Excellent	0.86 ≤ rating < 1.00
Good	0.65 ≤ rating < 0.86
Fair	0.44 ≤ rating < 0.65
Marginal	0.26 ≤ rating < 0.44
Unacceptable	0.00 ≤ rating < 0.26

CORA: CORrelation and Analysis.

Statistical Analysis

SPSS version 20.0 (SPSS for Windows, IBM Corp.) was used for all statistical analyses. In study 1, the Pearson correlation method was used for the correlation analysis

Table 3. Demographic Data of Patients with ITW

Patient	Sex	Age (yr)	Pre-cast			Cast off			Cast off timing (day)
			Height (cm)	Weight (kg)	BMI (kg/m^2)	Height (cm)	Weight (kg)	BMI (kg/m^2)	
1	F	10	145.9	47	22.1	146.7	48	22.3	7
2	F	10	136.2	47	25.3	136.6	49	26.3	7
3	F	7	148.8	28	12.6	148.5	28	12.7	14
4	F	7	142.9	49	24.0	142.7	50	24.6	7
5	F	8	140.4	46	23.3	140.3	46	23.4	7
6	F	12	158.7	64	25.4	159.1	65	25.7	7
7	M	9	146.1	49	23.0	146.9	50	23.2	7
8	M	11	144.5	42	20.1	145.2	43	20.4	7
9	M	10	126.2	52	32.7	126	52	32.8	14
10	M	9	133.7	31	17.3	134.1	31	17.2	7
11	M	11	140.8	48	24.2	141.6	48	23.9	7
12	M	12	152.8	34	14.6	152.9	35	19.2	14
13	M	9	148.5	40	18.1	149.2	40	18.0	7
14	M	15	144.7	46	22.0	144.6	47	22.5	7

ITW: idiopathic toe walking, BMI: body mass index.

between the MGA and OTS results, and the CORA score (PDB, 2017, Release 4.0.4) was used for the graph pattern comparison. In Study 2, a paired t-test was used to compare the results before and after corrective plaster bandage treatment. A $p < 0.05$ was defined as statistically significant.

RESULTS

Study 1: Comparison of Temporal Parameters

The temporal parameters obtained by the MGA system (treadmill walking) and OTS (ground walking) are shown in Table 4. The patient was examined at a comfortable walking speed paced by the patient (treadmill: 1.06 m/sec, ground walking: 1.10 m/sec). Although there was no statistically significant difference in temporal parameters, treadmill walking was associated with longer stride length and slower cadence compared to ground walking.

Study 1: Kinematic Results in the Sagittal Plane

Comparing the kinematic results in the sagittal plane, there was no statistically significant difference between the MGA systems and OTS at the pelvis, hip, and knee, but there was a statistically significant difference at the ankle in the stance minimum joint angle ($p = 0.019$) and swing phase range of angle ($p = 0.033$) (Table 5).

The kinematic graphs obtained by the OTS and MGA system were similar in overall shape, but showed a difference in angle at the initial contact, which made direct statistical processing of the 2 graphs unreasonable. Therefore, we only evaluated the overall correlation of the graphs. The pelvis showed a weak correlation (0.294) between the MGA system and OTS. On the other hand, the hip and knee showed a correlation of approximately 0.95 (hip joint: 0.967, knee joint: 0.949, ankle joint: 0.685) (Fig. 2).

Table 4. Comparison of Spatiotemporal Parameters

Variable	MGA (treadmill)	OTS (overground)	*p*-value
Velocity (m/sec)	1.06 ± 0.39	1.10 ± 0.12	0.601
Cadence (steps/min)	105.03 ± 12.1	123.92 ± 26.6	0.163
Stride length (m)	1.21 ± 0.42	1.07 ± 0.17	0.190
Stance (% cycle)	62.9 ± 5.78	61.6 ± 1.83	0.955
Swing (% cycle)	37.1 ± 5.78	38.4 ± 1.83	0.955
Double support (% cycle)	23.4 ± 10.52	21.3 ± 2.71	0.987

Values are presented as mean ± standard deviation.
MGA: markerless gait analysis, OTS: optical tracking system.

To more appropriately compare the correlation between the 2 graphs, the angle difference at the initial contact between the 2 methods was corrected to be the same. For this, the graph of the MGA system was vertically shifted by approximately +20° at the hip and –8° at the knee joint (Fig. 3).

The CORA score was calculated between the OTS kinematic graph and the corrected MGA graph (Table 6). The average CORA score of the 3 joints was 0.786, demonstrating a good grade. The CORA scores of the hip and knee joints were higher than 0.9, demonstrating an excellent grade and confirming that the correlation between the hip and knee joints was very high. On the other hand, the CORA score of the left ankle joint was 0.601, and that of the right ankle joint was 0.421, indicating that the correlation at the ankle joint was relatively low compared with that at the other joints.

Comparison of Convenience

In this study, the test time was 50 minutes for OTS and 10 minutes for MGA. OTS was performed first, and then MGA was performed, and the time including initial personal information preparation time, marker attachment time, and patient explanation was 50 minutes, and the actual walking time was about 10 minutes, so both tests were the same pure walking time. In addition, there was no need for the hassle of attaching markers and surface EMG leads. Compared to OTS, which requires various consumables such as marker tape, MGA does not require any consumables, so MGA could conduct gait analysis more conveniently in terms of time and cost.

Comparative Analysis between Pre- and Post-corrective Cast Treatment

In patients with ITW, the MGA kinematics before and after corrective casting showed differences in the results only at the ankle joint (Fig. 4). Statistical analysis was performed for the effect of corrective casting at the vertex of the graph of the first, second, and third rockers and the swing phase regarding the ankle joint, and there was a statistically significant difference at each point of the gait cycle (first ankle rocker: $p = 0.043$, second ankle rocker: $p = 0.049$, third ankle rocker: $p = 0.036$, swing phase: $p = 0.001$). In 14 pediatric patients, the joint angle was measured using an MGA and a protractor before corrective cast treatment and after removing the corrective cast on the 7th or 14th day (Table 7). When using MGA, the average ankle joint angles before cast application was 4.54°, compared to 10.11° after corrective cast treatment, and the difference value was 5.6°. When using a protractor, the av-

Table 5. Comparison of the Range of the Joint Angle on the Sagittal Plane in the Gait Cycle

Joint angle	Pelvis			Hip			Knee			Ankle		
	MGA	OTS	*p*-value	MGA	OTS	*p*-value	MGA	OTS	*p*-value	MGA	OTS	*p*-value
Initial contact	7.94 ± 2.64	10.50 ± 2.46	0.750	12.71 ± 3.63	32.39 ± 3.36	0.650	15.73 ± 7.24	7.13 ± 3.21	0.268	1.25 ± 5.87	–1.90 ± 4.17	0.084
Stance phase minimum	7.90 ± 2.68	9.54 ± 2.86	0.741	–3.46 ± 3.34	14.93 ± 3.44	0.420	6.86 ± 7.39	7.13 ± 4.13	0.172	–0.80 ± 5.87	–5.33 ± 5.13	0.019
Stance phase maximum	12.79 ± 2.10	10.57 ± 2.10	0.925	12.71 ± 2.10	32.39 ± 2.01	0.593	36.94 ± 6.03	39.96 ± 5.01	0.365	5.06 ± 5.97	10.62 ± 5.30	0.065
Swing phase minimum	7.95 ± 2.26	9.38 ± 2.62	0.638	–13.62 ± 2.27	–7.16 ± 2.72	0.762	4.60 ± 2.41	5.13 ± 3.31	0.104	–3.96 ± 7.25	–16.10 ± 4.52	0.039
Swing phase maximum	12.89 ± 2.05	10.49 ± 2.50	1.000	13.49 ± 2.05	34.99 ± 2.50	0.751	47.07 ± 2.57	61.20 ± 8.17	0.440	8.41 ± 5.34	2.90 ± 4.44	0.001
Stance phase range	4.89 ± 2.03	1.02 ± 2.30	0.548	16.17 ± 2.07	17.46 ± 2.70	0.749	30.08 ± 3.03	32.82 ± 4.03	0.913	5.86 ± 5.40	15.94 ± 6.13	0.226
Swing phase range	4.94 ± 2.04	1.11 ± 2.34	0.160	27.12 ± 2.31	42.15 ± 2.13	0.713	42.47 ± 5.01	56.07 ± 4.21	0.483	12.37 ± 5.12	19.00 ± 6.31	0.033
Total range	4.99 ± 2.05	1.19 ± 2.21	0.509	27.12 ± 2.26	42.15 ± 2.42	0.801	42.96 ± 4.36	56.07 ± 4.63	0.717	12.37 ± 4.13	26.71 ± 5.12	0.002

Values are presented as mean ± standard deviation.
MGA: markerless gait analysis, OTS: optical tracking system.

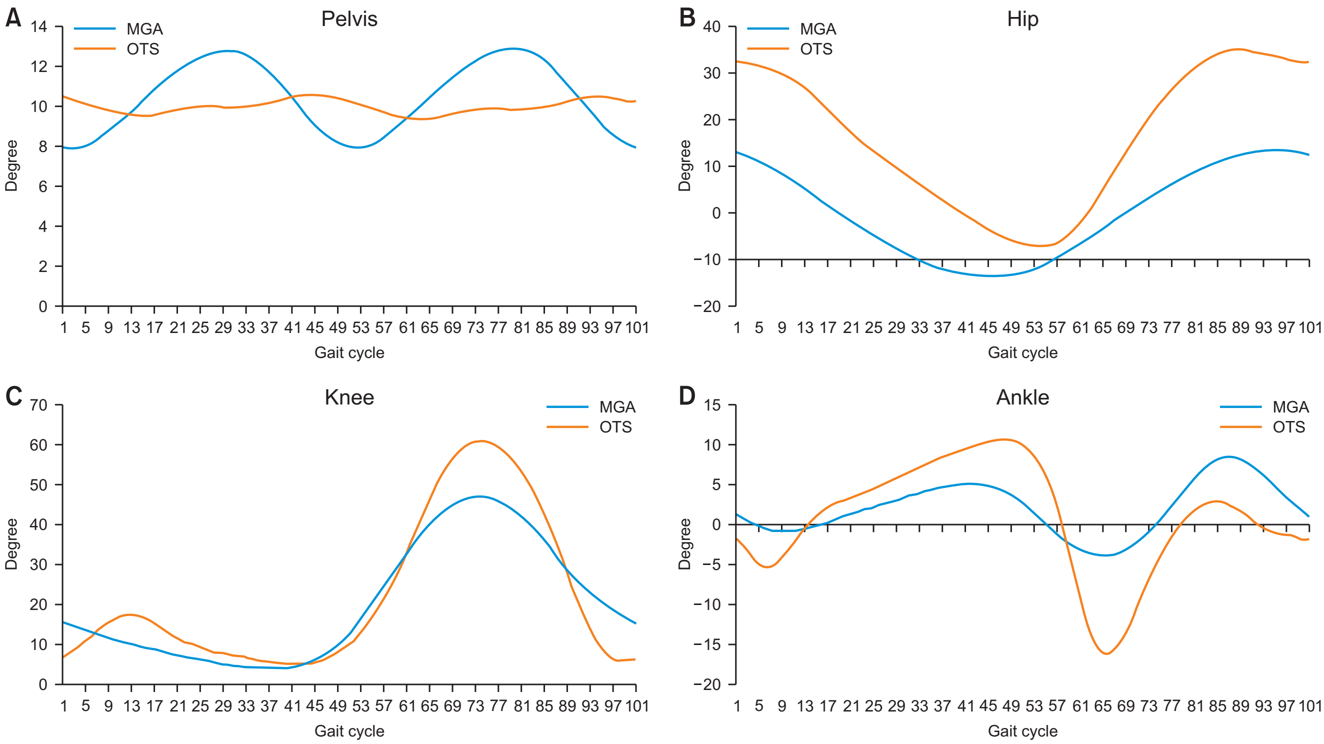

Fig. 2. (A-D) Kinematic graphs in the sagittal plane. Joint angles at the initial contact are different between markerless gait analysis (MGA) system and the optical tracking system (OTS).

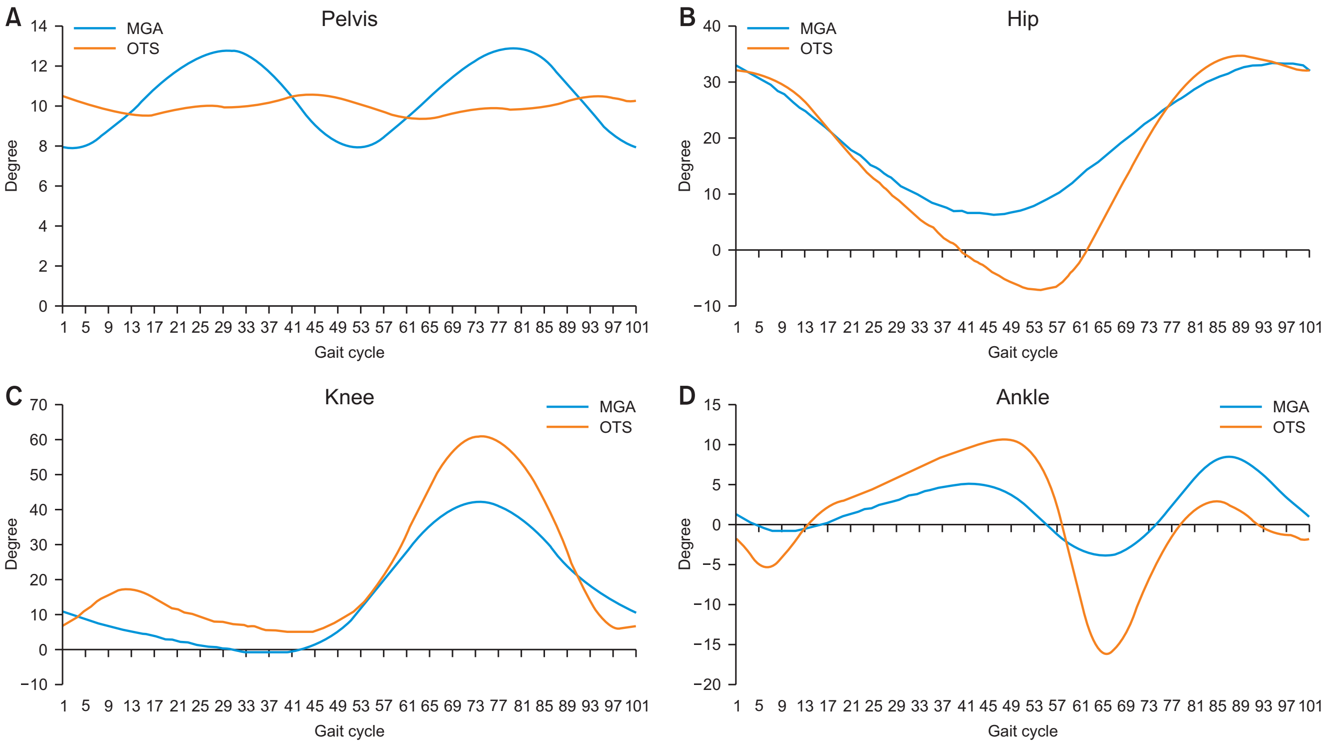

Fig. 3. Kinematic graphs in the sagittal plane after shifting of the knee and hip graphs. The graph of the MGA system was vertically shifted by approximately +20° at the hip and –8° at the knee joint to compensate for the angle difference at the initial contact between the 2 methods, which showed a high correlation between the methods. OTS: optical tracking system.

erage ankle joint angle before cast application was 3.2 and after corrective cast treatment was 11.8, and the difference value was 8.4°. When statistical analysis was performed using a paired test, the p-value was less than 0.001.

Table 6. Correlation of Joint Angles between 2 Gait Analysis Systems, Corrected MGA and OTS

Joint	CORA score				Rating
	Shape	Size	Phase	Total	
Left hip	0.916	0.946	0.998	0.944	Excellent
Right hip	0.883	0.898	0.998	0.915	Excellent
Left knee	0.950	0.770	0.998	0.917	Excellent
Right knee	0.926	0.818	0.998	0.917	Excellent
Left ankle	0.451	0.506	0.998	0.601	Fair
Right ankle	0.263	0.159	0.998	0.421	Marginal
Mean	0.732	0.683	0.998	0.786	Good

Rating is presented as 1.0 > excellent > 0.86 > good > 0.65 > fair > 0.44 > marginal > 0.26 > unacceptable > 0.0.
MGA: markerless gait analysis, OTS: optical tracking system, CORA: CORrelation and Analysis.

DISCUSSION

This paper analyzed the correlation between the gait data obtained by the OTS and MGA system for patients with various pathologic gaits. In addition, this paper compared the gait changes before and after treatment of patients with ITW using DH Walk, a recently developed MGA system, to examine whether the MGA systems developed to date can be used clinically.

However, since the OTS measures gait on flat ground, and the MGA system measures treadmill gait, these systems do not strictly measure gait in the same conditions. During ground walking, the floor is fixed, but on a treadmill, the floor moves.[10-13] Unlike ground walking, gait analysis on a treadmill can be performed even in a small space, but it requires a process for the subject to become adjusted to walking on it and at least 6 minutes for the subjects to find a comfortable walking speed.[14]

Many researchers have debated the similarity between treadmill and ground walking. Some authors have reported differences between the 2. Lee and Hidler[15] reported that there was a difference in sagittal plane joint moments and muscle activity between treadmill and overground walking, but there was very little difference between temporal gait parameters or kinematics. Van Ingen

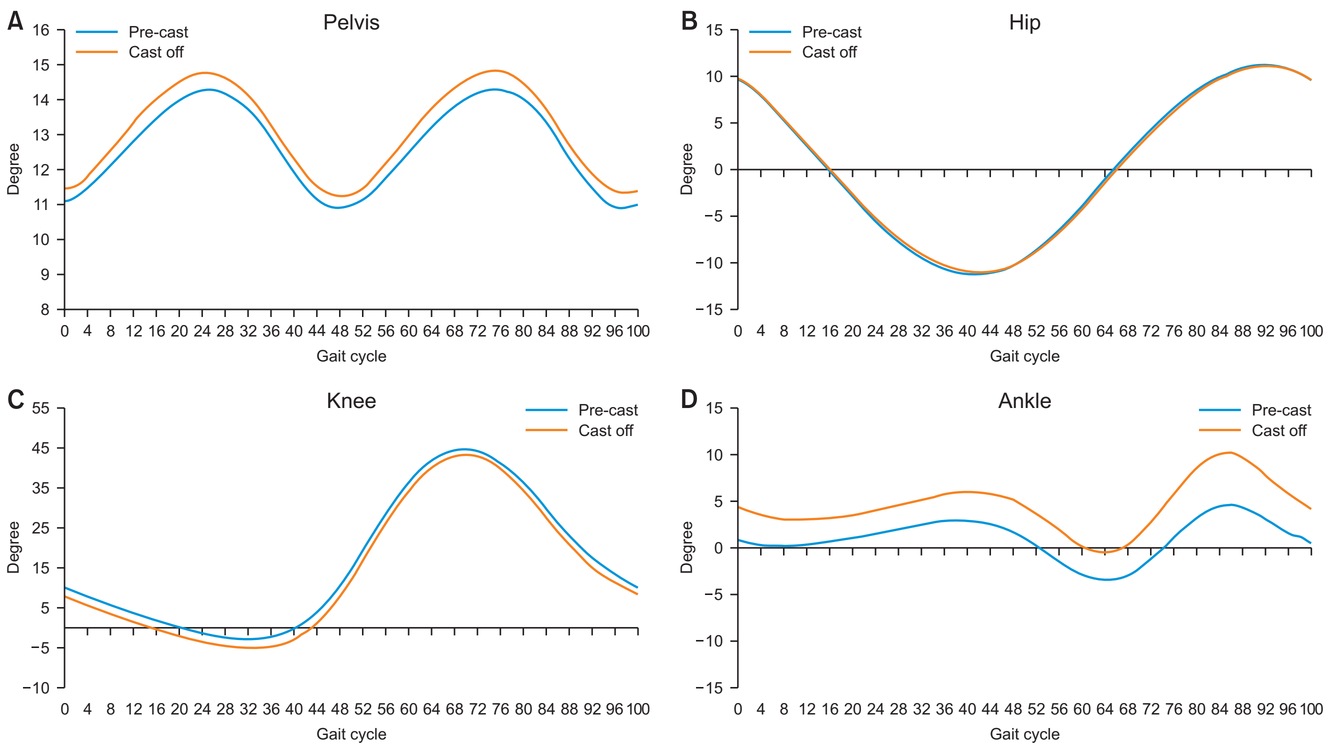

Fig. 4. (A-D) Sagittal plane ankle kinematics measured with DH Walk. Ankle dorsiflexion showed marked improvement after corrective casting in patients with idiopathic toe walking.

Table 7. Comparison of Ankle Joint Angle between the MGA System and Physical Examination Pre- and Post-cast

Patient	MGA (treadmill)		Physical examination	
	Pre (°)	Post (°)	Pre (°)	Post (°)
1	4.32	10.12	5	10
2	4.73	10.34	5	10
3	3.91	9.15	0	10
4	3.80	9.10	0	5
5	5.12	11.52	5	15
6	5.23	10.81	5	15
7	4.51	10.13	5	10
8	3.34	9.10	0	10
9	5.72	11.24	5	15
10	4.57	10.15	5	15
11	4.35	9.91	0	10
12	4.28	9.52	0	10
13	4.91	10.34	5	15
14	4.89	10.12	5	15
Mean	4.54	10.11	3.2	11.8
p-value	< 0.001		< 0.001	

MGA: markerless gait analysis.

Schenau[16] stated that the difference between the 2 gaits is highly related to the setting of the coordinate system, and if the coordinate system is properly set, the 2 gaits show no mechanical difference. The coordinate system contained whether the speed of the belt was constant, the angle of the slope was 0°, the motor power of the treadmill was powerful enough to withstand the maximum load of the belt, the feedback mechanism of the treadmill was fast enough to maintain the velocity so that the direction of the belt was constant, there was no roughness on the surface of the belt, and the texture was similar to the floor. In our study, the coordinate system was properly set.

Recently, many authors have reported that ground walking and treadmill walking are similar in terms of their temporal parameters and kinematics.[17] Since DH Walk was developed as a tool to measure treadmill walking, it may not be reasonable to directly compare the results with the OTS, which analyze ground walking. However, since most authors claim that the 2 types of walking show similar patterns, the method of this study comparing the 2 methods is considered appropriate. In the future, MGA systems will need to be measured on flat ground, resulting in more desirable research results.

The temporal parameters were generally similar between the 2 methods evaluated in this study, but in the case of treadmill walking, the stride length was slightly longer, and the cadence was slower. In the kinematic comparison between the OTS and MGA system, the graph pattern of each joint appeared similar, but the angle of initial contact was different. This was caused by the difference in calibration and the difference in the algorithm defining the joint angle between the OTS and MGA system. The joint angle in the OTS is defined as the difference between the measured spatial coordinates of the 2 segments, whereas in the MGA system, the joint angle of static capture is defined as 0 degrees, and the change is calculated during walking.

The kinematic graph in the sagittal plane showed an overall similar pattern and range of motion in the hip, knee, and ankle joints ($p = 0.685$), but the correlation at the ankle joint was relatively low compared with that at the hip and knee. This low correlation at the ankle joint might be due to either the relatively poor tracking accuracy of the MGA system for the foot or walking characteristics on the treadmill. Several MGA systems currently in commercial use take additional measures, such as attaching markers over the foot, to improve foot tracking accuracy. To examine patients with complex foot diseases, future studies are needed to increase the precision of ankle capture, such as installing additional cameras. Ceseracciu et al.[18] conducted a gait analysis according to the presence or absence of markers, and as in this study, the joint angle in the sagittal plane was similar regardless of the presence of markers. However, Moro et al.[19] reported that in gait analysis, the measurement value was statistically different in the maximum dorsiflexion of the ankle joint angle in the swing phase depending on the presence or absence of a marker. Since the difference in measurement value was small in our study, the method of performing gait analysis without a marker is also a sufficient alternative.

To date, the clinical gold standard technique for gait analysis is a method using motion capture systems and markers. However, such methods are relatively expensive and cumbersome, take long time to perform, and involve factors that interfere with the natural gait. For these reasons, over the past decade, studies have been conducted to develop markerless systems using various technologies. An MGA system does not require markers. It can save time and cost compared with an OTS and is free of marker artifacts.[20] Also, in our study, the MGA method reduced the time compared to OTS. An MGA system can perform gait analysis even on subjects with difficulty attaching markers.[21] A simple gait analysis system such as MGA might enable studies with large sample sizes that were not possible using a conventional OTS.

In a study evaluating the effect of the corrective casting on children with ITW, MGA showed statistically significant differences in specific gait cycles of sagittal ankle kinematics. This suggests that MGA could demonstrate the therapeutic effect of a corrective cast on the sagittal plane kinematics of the ankle joint.

This study has several limitations. First, the MGA study was conducted only with treadmill walking. Patients with a pathologic gait show a significant difference in compliance with treadmill use depending on the cause of the disease. Many children with GMFCS level 3 cerebral palsy were not suitable subjects for treadmill walking due to their unstable balance.

Second, the maximum distance that Azure Kinect can measure is 2.88 m based on wide field-of-view, which is not long enough to measure ground walking. To be used for ground walking in the future, newer technology is needed to overcome the limitations of the current camera with a narrow and short capture range. The use of several ToF cameras with post-processing software allows the elimination of blind spots of the foot and ankle that would hinder the analysis under the current method.

Third, this study could not analyze kinetics. To obtain kinetic data only with treadmill walking without a force plate, the calculation for kinetics during walking might be possible in the future based on a human body model system including the mass and dynamic properties of each segment and 3D joint position data.

Fourth, the sample size of this study was small and too many different disease groups of patients were included. To improve the clinical usefulness of the MGA system, a new gait analysis system and repeated experiments with a larger number of subjects are needed in the future to accumulate a large amount of data. It is also necessary to establish a standard suitable for MGA and to verify the research results.

As the OTS has been used as the current standard for gait analysis, there is clearly a need for MGA to refer to the OTS in its future development for clinical usage. The kinematics of MGA showed a good correlation at the hip and knee joints in the sagittal plane compared with the OTS. Further studies on the kinematics in the coronal and transverse planes of joints with relatively small ranges of motion changes during movement should also be performed.

In conclusion, the MGA system evaluated in this study showed comparable results compared to the conventional OTS for the temporal parameters and sagittal kinematics. Several limitations are expected to be solved in the future, such as the (1) calibration problem for the zero point, (2) limited gait analysis during treadmill walking, (3) use of only 1 camera with a short capture range, (4) relatively low correlation of ankle kinematics, and (5) limited software of DH Walk in obtaining kinetic data.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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