INTRODUCTION

Previous studies have shown the usefulness of three-dimensional gait analysis (3DGA) for evaluating gait disorder, the time-consuming measurement process and space requirement has hampered its use in the clinical setting. The aim of this study was to examine the feasibility of a simplified 3DGA system for stroke patients. Methods: Thirteen pairs of stroke patients and age- (± 1 year), gender-, and gait speed- (± 0.5 m/s) matched controls were drawn from the Fujita Health University gait analysis database. 3DGA was performed using the KinemaTracer® treadmill gait analysis system. Comparisons of the spatiotemporal and kinematic parameters were performed between stroke patients and matched controls. The correlations between items from the Wisconsin Gait Scale (WGS) and 3DGA data in stroke patients were also investigated. Results: 3DGA measurements clearly showed reduced toe clearance, hip flexion, and knee flexion in stroke patients compared with the matched controls. In contrast, significant increases were observed in hip elevation, shoulder elevation, shoulder lateral shift, and step width in stroke patients. For the four items drawn from the WGS, a significant correlation with three 3DGA parameters was observed: stance time on the impaired side, stance width, and knee flexion from toe off to midswing. Conclusions: In this study, significant differences in gait parameters of stroke patients and age-, gender-, and speed-matched controls were found using a simplified 3DGA system. A significant correlation with WGS was also observed. These results support the validity of the clinical measurement of gait parameters using a simplified 3DGA system.

Key Words: gait analysis; hemiplegic gait; stroke
of measurement compared to the systems used for research. Consequently, simplified systems for the clinical evaluation of gait disorders need to be validated.

In this study, we investigated the feasibility of using a simple 3DGA system for the clinical analysis of gait in stroke patients. We evaluated the gait patterns of 13 stroke patients with hemiparesis and compared them with age-, speed-, and gender-matched controls. The differences between controls and patients are presented in holistic illustrations, and quantitative analysis was used to investigate whether this approach can determine the specific features of individual gait patterns of hemiparetic patients, thereby depicting the differences between controls and patients. Further comparisons were made between the parameters evaluated by the simplified 3DGA system and related parameters from the Wisconsin Gait Scale (WGS), which is a scale used for clinical gait evaluation.

### Methods

#### Subjects

Thirteen pairs of stroke patients and age- (± 1 year), gender-, and gait speed- (± 0.5 m/s) matched controls were drawn from the Fujita Health University gait analysis database. The inclusion criteria for stroke patients were (1) hemiplegia, (2) being able to walk on a treadmill independently, and (3) not being dependent on assisting devices (e.g., handrails, canes, or orthotics). Of the 13 hemiplegic patients, 10 were men and 3 were women, and 7 had right hemiplegia and 6 had left hemiplegia; the average age was 48 ± 15 years. 3DGA was carried out between 200 and 5453 days (median 1176 days) after the onset of stroke. The average total score of the stroke impairment assessment set (SIAS) was 9.2 ± 1.2. The average total WGS score was 22.9 ± 3.5. The average gait speed on a treadmill was 2.3 ± 0.7 km/h. The demographic variables of the hemiparetic patients are shown in Table 1.

#### Measurement

3DGA was performed using a simplified gait analysis system, the KinemaTracer® treadmill gait analysis system (Kissei Comtec Co., Ltd., Matsumoto, Japan). A total of 12 markers (30 mm in diameter) were placed bilaterally on the acromion (shoulder marker), iliac crest (pelvis marker), great trochanter (hip marker), lateral femoral epicondyle (knee marker), lateral malleolus (ankle marker), and the fifth metatarsal head (toe marker). The subjectively comfortable gait speed was calculated from a 10-m walk test, and the treadmill gait speed was set according to the ground gait speed. Subjects were not allowed to use a handrail or orthosis. Videos were recorded at a sampling frequency of 60 Hz and a measuring time of 20 s.

Heel-strike and toe-off events were determined automatically by the system based on the toe and ankle marker trajectories. Two experienced physical therapists checked the accuracy of the timing and made adjustments if there was an error. From these events, the cadence (steps/min), stride length (m), step width (m), and the durations of double stance and single stance (the seconds of gait cycle duration) were calculated.

The elevations of the toe, knee, hip, and shoulder markers; the lateral displacement of the ankle and shoulder markers; and the angle changes (hip, knee, and ankle) on the paretic side were calculated. The values for elevations of the toe, knee, hip, and shoulder markers were obtained from the Z coordinate of the appropriate marker. The shoulder and foot

### Table 1. Demographic and baseline characteristics of the subjects

| Characteristic          | Stroke          | Controls        | P    |
|-------------------------|-----------------|-----------------|------|
| Age (years)             | 48.2 ± 15.0     | 48.2 ± 15.2     | 0.58 |
| Male                    | 10              | 10              |      |
| Female                  | 3               | 3               | 1.00 |
| Days since stroke       | 200–5453 (median 1176) |               |      |
| Right hemiparesis       | 7               |                 |      |
| Left hemiparesis        | 6               |                 |      |
| Treadmill speed (km/h)  | 2.3 ± 0.7       | 2.3 ± 0.6       | 0.48 |
| SIAS motor score        | 9.2 ± 1.2       |                 |      |
| Wisconsin gait scale    | 22.9 ± 3.5      |                 |      |

SIAS: Stroke impairment assessment set
RESULTS

Representative LOPs of the stroke patients andagematched controls are shown in Fig. 1. The LOPs provide a holistic view of gait patterns to illustrate the features of hemiparetic gait. The arrows indicate the gait abnormalities frequently observed in hemiparetic patients.

The spatiotemporal parameters for stroke patients and matched controls are shown in Table 2. There were no significant differences between the two groups in stride length, cadence, and duration of the stance phase. However, significant shortening of the single stance phase (P = 0.0031) and a prolonged swing phase (P = 0.0498) were observed in the stroke patients.

Table 3 shows the kinematic parameters of the two groups and indicates the significant differences between the groups. The stroke group showed reduced toe clearance (3.6 vs 8.6 cm, P < 0.0001), hip flexion (1.7 vs 7.9 cm, P = 0.0083), and knee flexion (14.3 vs 55.4 cm, P < 0.0001) in the paretic limb. In contrast, a significant increase was observed in hip elevation (3.8 vs 0.2 cm, P < 0.0001), shoulder elevation (4.0 vs −0.3 cm, P < 0.0001), shoulder lateral shift (4.2 vs 0.6, P = 0.0009), and step width (29.2 vs 23.3 cm, P = 0.0004), which are known to be compensatory movements frequently found in stroke patients.

A comparison of the WGS subscales and the corresponding parameters evaluated by the 3DGA system is shown in Fig. 2. The following subscales in which the number of cases is two or more for every response option was employed for the analysis: stance time on the impaired side, stance width, knee flexion from toe off to midswing, and toe clearance.

Significant correlations between 3DGA parameters and WGS subscales were observed for stance time on the impaired side (−0.55, P = 0.0175), stance width (0.47, P = 0.0417), and knee flexion from toe off to midswing (−0.62, P = 0.0061). Toe clearance (−0.36, P = 0.112) presented a weak correlation with the corresponding 3DGA parameter, and the correlation was not significant in the present investigation.

DISCUSSION

In this study, the gait pattern of hemiparetic patients and healthy subjects was compared, and significant differences were found between the two groups. The quantification of various parameters illustrated reduced limb movement (e.g., knee and hip flexion) as a result of paresis and an increase in compensatory movements (i.e., hip and shoulder elevation and shoulder lateral shift). Despite the small sample size, significant correlations between observational WGS scores and 3DGA kinematic parameters were observed. The LOP provides a holistic overview of gait patterns composed from the combination of these changes.

Our results are consistent with previous studies describing the features of gait patterns of hemiparetic patients (most typically referred to as a stiff knee gait) characterized by reduced knee flexion and the presence of hip elevation and circumduction combined with a shortened single-stance phase and a prolonged swing phase.1,13,14 In addition, the significant differences found between stroke patients and age-, gender-, and speed-matched controls, together with the significant correlations with WGS subscales, support the construct validity of the measurement method to evaluate abnormal gait patterns in clinical settings.

A number of sophisticated studies using 3DGA systems have shown the gait mechanisms of healthy subjects and patients suffering from gait disorders. Despite the success and contribution of these studies to gait analysis research, 3DGA systems are still not widely used in daily clinical practice.

There were no significant differences between the stroke and control groups investigated using the Mann–Whitney U-test. The Kendall rank correlation coefficient was calculated for correlation analysis. Nonparametric statistics were used because of the small sample size (n = 13). A P-value of less than 0.05 was considered statistically significant.
Fig. 1. Representative holistic Lissajous overviews of gait patterns in stroke patients and in age-, gender-, and speed-matched controls: A–C show the gait pattern of a healthy control, whereas D–F show that of a stroke patient. The trajectory of markers is shown in the horizontal plane (A, D), sagittal plane (B, E), and coronal plane (C, F). In stroke patients, hip elevation (black arrows), shoulder lateral shift (gray arrow), and circumduction (white arrows) were observed. Toe clearance reduction (dashed white arrow) can also be seen.
practice. The main methods used to evaluate patients in daily clinical practice are visual observation and clinical scoring. Considering the reliability problems associated with visual observations reported in several specific situations, the use of 3DGA in clinics would appear to be a beneficial option for clinicians. However, there are several reasons why 3DGA is not used for clinical gait analysis. The major reasons are space and time limitations and safety considerations. Research-based 3DGA systems usually require a considerable amount of preparation time to run the system and to attach multiple markers to the patient. In addition, gait analysis systems usually require a large space to evaluate ground walking. Because the many markers have to be tracked by a camera, supervision of the patient by a stand-by therapist is not practical. In combination, these disadvantages limit the application of gait analysis using 3DGA systems.

These limitations result from the pursuit of accurate measurements in a research setting. However, the gait speed of patients with gait disorders is limited, and the focus of clinical observations is on relatively coarse movements. Consequently, the clinical analysis of patients with gait disorders may not need the accuracy to appraise the precise high-speed motions associated with the measurement of sports performance. Therefore, in this study, we employed a simple 3DGA system with a minimal subset of markers and fewer cameras than is commonly used. Moreover, this system analyses the gait of subjects on a treadmill, which enables a stand-by therapist to supervise. Although previous studies have shown that the use of a treadmill affects gait patterns to some extent, it tends to accentuate the gait asymmetry, which makes it easier to detect a gait disorder.

The size of the markers used in this study was 30 mm in diameter. This is larger than those frequently used. In previous studies, the marker size was shown to correlate with a tendency toward increased measurement accuracy. The use of relatively large markers in this system could potentially contribute to improved measurement accuracy. The accuracy of the gait abnormality evaluations made in the current study must be evaluated further, the significant differences found between stroke patients and healthy subjects warrants further research to explore the feasibility of this kind of simplified clinically oriented 3DGA system.

Another problem that prevents the use of 3DGA in clinics is the difficulty of interpreting the results. Usually, gait disorders are combinations of several movement abnormalities, and understanding such disorders using the many graphs

### Table 2. Spatiotemporal parameters

|                  | Stroke          | Control         | P    |
|------------------|-----------------|-----------------|------|
| Cadence (cm)     | 103.8 ± 20.6    | 105.9 ± 15.7    | 0.8003|
| Stride (cm)      | 73.4 ± 21.7     | 73.9 ± 19.9     | 0.9945|
| Stance phase (s) | 0.75 ± 0.16     | 0.78 ± 0.15     | 0.5686|
| Single stance (s) | 0.29 ± 0.06   | 0.38 ± 0.05     | 0.0031|
| Double stance (s)| 0.45 ± 0.12     | 0.40 ± 0.11     | 0.2291|
| Swing phase (s)  | 0.45 ± 0.09     | 0.37 ± 0.05     | 0.0498|

* P < 0.05, ** P < 0.01

### Table 3. Kinematic parameters

|                  | Stroke          | Controls        | P    |
|------------------|-----------------|-----------------|------|
| Toe clearance (cm) | 3.6 ± 1.7       | 8.6 ± 2.9       | < 0.0001|
| Foot lateral shift (cm) | 7.3 ± 3.4 | 5.0 ± 1.7       | 0.0176|
| Knee elevation (cm) | 4.5 ± 1.2       | 3.7 ± 1.5       | 0.1971|
| Hip elevation (cm)  | 3.8 ± 1.3       | 0.2 ± 0.6       | < 0.0001|
| Shoulder elevation (cm) | 4.0 ± 1.1 | -0.3 ± 0.6      | < 0.0001|
| Shoulder lateral shift (cm) | 4.2 ± 2.5 | 0.6 ± 1.3      | 0.0009|
| Hip flexion (°) ** | 1.7 ± 8.3       | 7.9 ± 6.7       | 0.0083|
| Knee flexion (°) ** | 14.3 ± 17.4     | 55.4 ± 9.3      | < 0.0001|
| Ankle plantar flexion (°) | 6.2 ± 8.3 | 10.1 ± 6.4     | 0.1343|
| Step width (cm) ** | 29.2 ± 3.6      | 23.3 ± 2.5      | 0.0004|

* P < 0.05, ** P < 0.01
generated during analysis requires experience. The LOP, as shown in this study, helps to understand intuitively the holistic patterns of patients’ gaits and promotes a focus on specific problems, as shown in previous studies.\(^{10}\) Moreover, not only measuring the displacements of individual markers but also developing clinical indices for abnormal gait patterns may facilitate the understanding of a gait disorder following stroke.\(^{21,22}\)

There are several limitations in this study. The item “toe clearance” in WGS had a non-significant correlation with toe elevation as measured by the 3DGA system. This weak correlation could have resulted from the small sample size and the relatively low reliability of the observational evaluation of toe clearance compared with that of other parameters, as has been shown in previous studies.\(^{11,23}\) In this study, the marker on the fifth metatarsal head was used as the toe marker, and, as a result, the foot position during the swing phase could have had some influence on the measurements obtained. The application and potential limitations of measurement using this method should be further investigated. Nonetheless, these results, in combination with a simplified 3DGA system and the use of LOPs, may encourage the practical, everyday use of 3DGA in rehabilitation clinics.

**CONCLUSION**

Comparisons between the gait patterns of stroke patients and age-, gender-, and speed-matched controls evaluated using a simplified 3DGA system showed significant differences between the two groups, indicating the validity of clinical measurements made using a simplified 3DGA system. The results of the current study support the clinical use of 3DGA for the evaluation of hemiparetic gait and encourage more detailed analysis to validate the application of 3DGA in clinical settings.
CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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