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Abstract

Background

Restoration of walking ability is the major goal of rehabilitation for stroke patients with hemiplegia. However, assessment methods are based on subjective evaluation, and no established objective assessment method exists that is clinically feasible. This study aimed to determine whether accelerometers could be used as clinically feasible objective assessment tools for predicting walking ability in stroke patients with hemiplegia.

Methods

Participants included 36 stroke patients with hemiplegia who were able to walk (group C) and 40 healthy individuals (group N). Wearable accelerometers were attached at the seventh cervical (C7) and third lumbar vertebral (L3) levels. Acceleration, in three axial directions (mediolateral, vertical, and anteroposterior), was measured during walking. Root mean square values were calculated and used as indices for cervical and lumbar sway. Associations between these values and the degree of gait independence, measured using the Functional Ambulation Classification (FAC) score, were evaluated.

Results

The cervical/lumbar sway significantly increased with decreasing degrees of gait independence (from groups with FAC5 to FAC4 and FAC3) in all three directions in group C. In group N, the cervical sway was smaller than the lumbar sway in all three directions. In group C, the cervical sway increased with decreasing degrees of gait independence; however, in the group with FAC3, the cervical sway was greater than the lumbar sway, showing a reverse phenomenon.

Conclusions

These results revealed an association between body sway and degree of gait independence and

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demonstrated that evaluating cervical/lumbar sway using wearable accelerometers helped accurately and objectively assess walking ability.

Key Words: Accelerometer; Gait analysis; Hemiplegia; Functional Ambulation Classification

Introduction

It is well-known that many stroke patients with hemiplegia have abnormal gait (i.e., an abnormal walking pattern) even after they become capable of walking. Walking with an abnormal gait may lead to joint deformity and an increase in risk of falls. Therefore, it is important for stroke patients with hemiplegia to develop a normal or near-normal and stable gait as early as possible. To achieve this, an accurate and objective assessment of walking ability is needed; however, in the current clinical setting, the assessment of walking ability is based on subjective evaluation techniques, such as observation by the examiner.

In recent years, the method of using a wearable accelerometer has received attention as an objective assessment tool to predict walking ability[1]. In this method, a wearable accelerometer is typically attached to the lumbar spine near the body's center of gravity, and acceleration of the body's center of gravity is measured during walking and analyzed. However, few studies have evaluated the acceleration at regions other than the back. Although Sugawara et al reported correlations between acceleration at the cervical and lumbar spine during walking and severity of hemiplegia (i.e., impairment) in patients with stroke[2], to our knowledge, no studies have investigated the association between the acceleration of the body's center of gravity during walking and the degree of gait disturbance (i.e., disability).

This study aimed to evaluate the associations between cervical/lumbar sway during walking and walking ability using a wearable accelerometer in stroke patients with hemiplegia, and to determine whether the accelerometer could be used as a clinically feasible objective assessment tool to predict walking ability in such patients.

Methods

Participants included 36 stroke patients with hemiplegia with no evidence of joint disorder in the legs who were able to sufficiently understand the oral explanation and were able to walk along a 16-m straight course without assistance. Forty healthy individuals without gait disturbances were also included as controls. This study was approved by the ethics committee of our institution (Approval Number #1). Informed consent was obtained from each participant after full written and oral explanation of the objectives of the study and the methodologies involved.

The stroke patients with hemiplegia (group C) consisted of 29 men and 7 women, with a mean age of 69.9±9.1 years. The diagnoses were cerebral infarction in 25 patients and cerebral hemorrhage in 11 patients. Hemiplegia was right-sided in 26 patients and left-sided in 10 patients. The degree of hemiplegia, based on the Brunnstrom Recovery Stages for the lower extremities, was Ⅳ (movement deviating from basic synergies) in 8 patients, Ⅴ (movement independent of basic synergies) in 16 patients, and Ⅵ (near-normal coordinated movement) in 12 patients. The healthy individuals (group N) consisted of 26 men and 14 women, with a mean age of 27.7±7.7 years.

The degree of gait independence was rated according to the Functional Ambulation Classification (FAC) score of the Hospital at Sagunto. The FAC is a tool to evaluate functional walking ability based

Table 1. Functional Ambulation Classification (FAC)

0: Nonfunctional Ambulator	Patient cannot ambulate, ambulates in parallel bars only, or requires supervision or assistance from more than one person to ambulate safely outside parallel bars.
1: Ambulator-Dependent for Physical Assistance	Patient requires manual contact of no more than one person during ambulation on level surfaces to prevent falling. Contact is continuous and necessary to support body weight as well as to maintain balance or assist coordination.
2: Ambulator-Dependent for Physical Assistance	Patient requires manual contact of no more than one person during ambulation on level surfaces to prevent falling, consisting of continuous or intermittent light touch to assist balance or coordination.
3: Ambulator-Dependent for Supervision	Patient can ambulate without manual contact from another person but, for safety, requires standby guarding of no more than one person because of poor judgement, questionable cardiac status, or the need for verbal cuing to complete the task.
4: Ambulator-Independent, Level surfaces only	Patient can ambulate independently on level surfaces, but requires supervision or physical assistance to negotiate any of the following: stairs, inclines, or non-level surfaces.
5: Ambulator-Independent	Patient can ambulate independently on nonlevel and level surfaces, stairs and inclines.

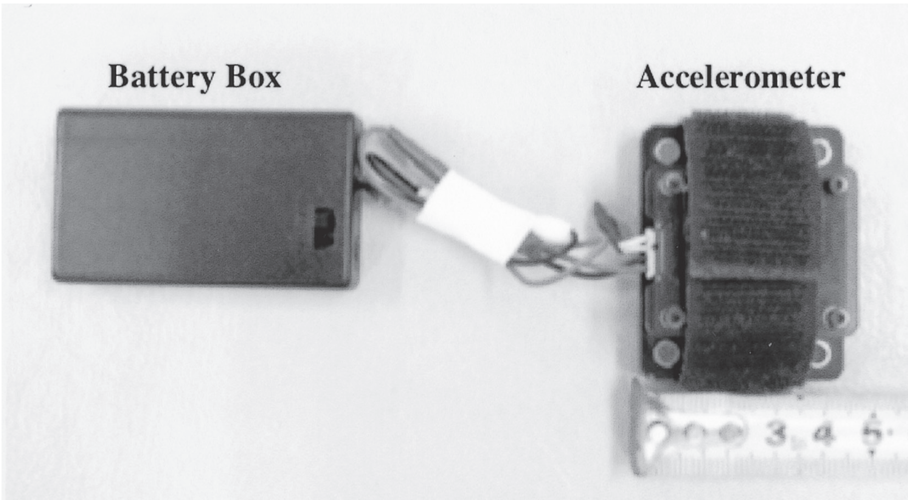

Figure 1. A wearable accelerometer, IMU-Z (ZMP Inc.), with a sensor unit size of 42.0×52.5×20.5 mm and a weight of 35g, was attached to the cervical and lumbar spine of each participant.

on observation, using a 6-point scale ranging from 0 to 5, with greater numbers indicating better walking ability[3] (Table 1). The degree of gait independence in group C was FAC3 in 6 patients (group FAC3), FAC4 in 11 patients (group FAC4), and FAC5 in 19 patients (group FAC5).

A wearable accelerometer, IMU-Z (ZMP Inc.), with a sensor unit size of 42.0×52.5×20.5 mm and a weight of 35g, was attached to the cervical and lumbar spine of each participant, and the acceleration during walking at the cervical and lumbar spine were measured. The measurements were uploaded to a computer (the host terminal) via Bluetooth, thereby allowing for a real-time measurement of acceleration without interfering with walking (Fig. 1).

The accelerometer was attached to the neck at the level of the seventh cervical vertebra (C7) and to the hip at the level of the third lumbar vertebra (L3). C7 was chosen because it is easy to identify this vertebra tactually. L3 was chosen because it is closer to the body's center of gravity and moves in parallel with the body's center of gravity, with minimal horizontal rotation[4]. Each accelerometer was fixed using an elastic belt, and the absence of potential influence of the elastic belt on performance was confirmed by asking participants about the presence of a feeling of restraint while attaching the device every time. Participants wore their own comfortable shoes and were allowed to use a lower extremity orthosis, if needed, during the walking test; however, they were not allowed to use a cane. During the test, all obstacles that might interfere with walking were removed from the environment so that participants could concentrate on walking. In addition, for security purposes, another therapist (non-examiner) stood by the participant during the test in case of unexpected accidents. Participants walked at their preferred speed.

The walking course included two 3-m sections, each for warm-up and cool down, and a 10-m course for speed measurements, with a total of 16 m. Root mean square (RMS) values were calculated from the acceleration data in the three axial directions obtained during steady-state walking on the 10-m course. The RMS indicates the mean amplitude of the signal waveforms, and the RMS calculated from the acceleration data during walking indicates the degree of body sway during walking; higher values reportedly indicate greater sway[5-7]. The RMS value obtained from the accelerometer attached to C7 was used as the index of cervical sway, while that obtained from the accelerometer attached to L3 was used as the index of lumbar sway. The RMS value is known to be proportional to the square of walking speed, which may result in greater values. Therefore, the influence of walking speed was eliminated by dividing the obtained RMS by the square of walking speed[8]. Furthermore, the influence of body height was eliminated by dividing the value by body height.

Statistical analysis of the relationship between the degree of gait independence and the cervical/lumbar RMS values was performed using analysis of variance with a significance level of $p<0.05$. Statistical analyses were performed using statistical software [R].

Results

The mean RMS values in group N (Control) and group C (FAC 5, 4, 3) for the cervical and lumbar spine were shown in the table 2: in the mediolateral (ML) direction, the vertical (V) direction, and the anteroposterior (AP) direction, respectively. The differences were statistically significant for all items by analysis of variance (Table 2).

Furthermore, a comparison between cervical and lumbar RMS values showed that the former was lower than the latter in all three axial directions in group N, and the differences were statistically significant. In group C, the cervical RMS values increased with decreasing degrees of gait

Table 2. The RMS values in group N (Control) and group C (FAC 5, 4, 3) (mean±SD), and P values by analysis of variance.

	ML (C7)	ML (L3)	V (C7)	V (L3)	AP (C7)	AP (L3)
Control	0.034±0.008	0.049±0.013	0.069±0.010	0.087±0.022	0.037±0.010	0.068±0.021
FAC5	0.079±0.027	0.109±0.046	0.122±0.037	0.149±0.050	0.069±0.027	0.108±0.038
FAC4	0.203±0.091	0.203±0.067	0.238±0.102	0.267±0.099	0.151±0.176	0.176±0.074
FAC3	0.379±0.251	0.328±0.103	0.383±0.180	0.359±0.107	0.318±0.228	0.307±0.144
P value	3.06E-16	1.48E-21	3.29E-18	6.78E-20	2.46E-13	1.27E-15

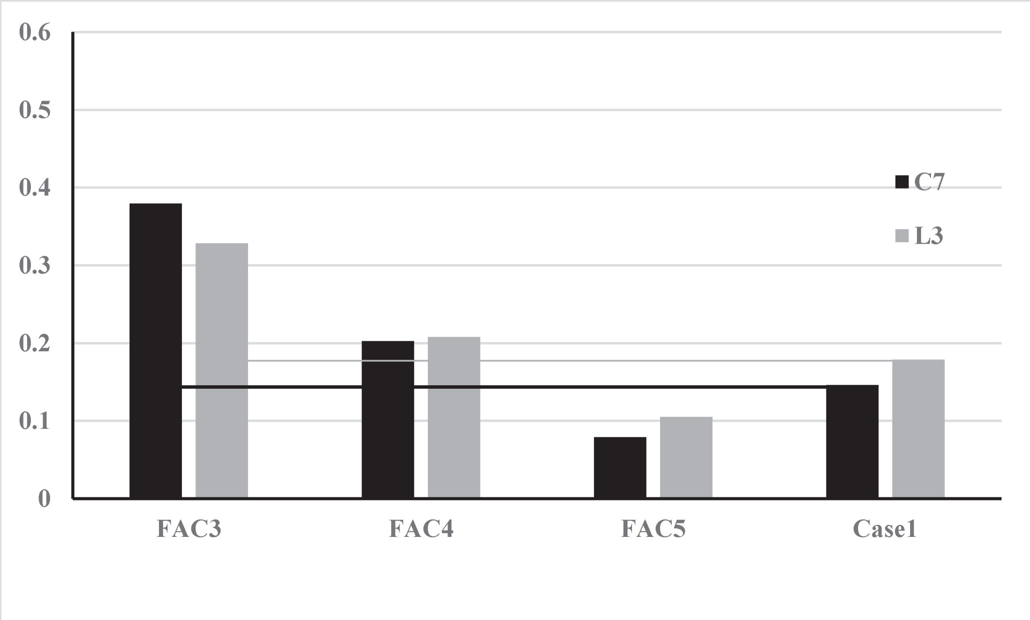

Figure 2. RMS values in ML direction of representative case are intermediate between FAC4 and FAC5, and in particular, the value of lumbar spine is close to the value of FAC4.

Table 3. FAC assessment for representative case by each therapist (* :standard)

Therapists (Years of experience)	FAC
A* (30 years)	4
B (9 years)	4
C (6 years)	5
D (5 years)	5
E (3 years)	5
F (3 years)	5
G (2 years)	4
H (2 years)	3
I (1 year)	4

independence; and cervical RMS value was higher than the lumbar RMS value in group FAC3, showing a reverse phenomenon.

Here, we report a representative case (Case 1). The patient was a 76-year-old man. He had right hemiplegia due to cerebral infarction and his Brunnstrom recovery stage for the lower extremities was V.

The mean RMS values for the cervical and lumbar spine obtained from the accelerometer in Case 1 were as follows: in the ML direction, 0.145 and 0.178; in the V direction, 0.162 and 0.256; and in the AP direction, 0.079 and 0.133, respectively. A comparison of these values with the mean RMS values of group C (according to the FAC score) in all three axial directions showed that the RMS values of Case 1 were within ±1SD of the mean RMS of group FAC4; moreover, it was lower than that of group FAC3, and outside the range of values of group FAC5. These findings suggested that the status of Case 1 corresponded to that of group FAC4 (Fig. 2 : the result in ML direction).

Furthermore, the degree of gait independence of representative case was evaluated by 10 physical therapists (the mean work experience duration was 6.2 years, ranging from 1 to 30 years) using the FAC score. Although there were variations among therapists in terms of the results, the patient status was rated as FAC4 by all physical therapists with sufficient experience. Thus, the result obtained from the RMS values coincided with that obtained from physical therapists with sufficient experience (Table 3).

Discussion

Walking is an extremely complex movement. Bipedal locomotion—walking on two legs in an upright position—is a dynamic repetitive movement with a regular pattern, in which the lost balance is restored by using two legs alternatively. To achieve walking, control of the trunk (central part of the body) is necessary; thus, stability of the trunk is important for achieving smooth movement of the upper and lower extremities. It is therefore considered that decreased trunk function leads to decreased walking ability. In addition, the anatomical structure for controlling trunk motion is extremely complex[9].

The results of this study showed that body sway during walking (both cervical and lumbar spine) significantly decreased with increasing degrees of gait independence in all three axial directions (ML, V, and AP). The findings showed an association between body sway during walking and walking ability.

In group N, the cervical sway was significantly smaller than the lumbar sway in all three axial directions. In group C, the cervical sway increased with decreasing degrees of gait independence; moreover, in group FAC3, the cervical sway was greater than the lumbar sway, showing a reverse phenomenon. The results showed that the characteristic features of body sway in group FAC3 were different from those of healthy individuals. Increased cervical sway in group FAC3 was considered one of the reasons for these patients requiring stand-by assistance.

FAC3 is described as follows: "Patients can walk independently on level ground but require stand-by help from one person for security purposes (walking with stand-by assistance)"[2]. A study in healthy elderly individuals using a motion sensor indicated a significant difference in the displacement range of body sway during walking between the lower part of the trunk and the head, and that the trunk sway was attenuated in the process of its transmission to the head. The findings support the notion that the higher cervical sway in comparison to the lumbar sway in group FAC3, in contrast to the pattern observed in healthy individuals, was one of the reasons for these patients requiring stand-by assistance while walking.

Group FAC4/FAC5 showed smaller cervical/lumbar sway in comparison to group FAC3; moreover, in contrast to group FAC3, group FAC4/FAC5 showed smaller cervical sway than lumbar sway—a body sway pattern similar to that of healthy individuals. We believe that the decrease in cervical/lumbar sway, as well as the relative decrease in cervical sway compared with lumbar sway, leads to an improvement in safety and independence of gait.

In general, walking ability is assessed by observing walking behavior and by detecting the presence/absence of abnormal gait pattern. Observational assessment of walking can yield acceptable results if it is performed in a systematic manner; however, detailed measurements may be inconsistent among examiners[9]; some researchers may consider that the inter-rater reliability is low owing to the differences in "observational perspective" and "subjective scale".

This study showed that cervical/lumbar sway during walking, measured using a wearable accelerometer, significantly differed according to the degree of gait independence. It was demonstrated that the evaluation of cervical/lumbar sway using the wearable accelerometer allows accurate and objective assessment of walking ability, and the wearable accelerometer can be used as a clinically feasible, objective assessment tool.

Some limitations of the study must be considered while interpreting the study results. There was a large difference in the mean age of group C (stroke patients with hemiplegia) and group N (healthy individuals), which may have influenced the results. Walking ability, and dynamic and static balance are reportedly reduced in older people compared with younger people[10,11]. Further studies using an age-matched control group are needed. In addition, the time dependent changes in the degree of gait independence in stroke patients with hemiplegia were not examined in this study, and further study of this issue is also needed.

This study evaluated the associations between cervical/lumbar sway during walking and the degree of gait independence using a wearable accelerometer in stroke patients with hemiplegia.

The cervical/lumbar sway significantly increased in all three axial directions (ML, V, and AP) with decreasing degrees of gait independence [from group FAC5 (completely independent) to FAC4 (independent only on plain ground) and FAC3 (walking with stand-by assistance)] in both group C (stroke patients with hemiplegia) and group N (healthy individuals). Furthermore, the cervical sway increased with decreasing degrees of gait independence; in addition, in group FAC3, the cervical sway was greater than the lumbar sway, showing a reverse phenomenon.

The results from this study revealed associations between cervical/lumbar sway during walking and the degree of gait independence, and demonstrated that the wearable accelerometer could be used as a clinically feasible objective assessment tool for predicting walking ability.

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