Gait Feature Vectors for Post-stroke Prediction using Wearable Sensor

Seunghee Hong¹, Damee Kim², Hongkyu Park³, Young Seo⁴, Iqram Hussain⁵ Se Jin Park⁶†

Abstract

Stroke is a health problem experienced by many elderly people around the world. Stroke has a devastating effect on quality of life, causing death or disability. Hemiplegia is clearly an early sign of a stroke and can be detected through patterns of body balance and gait. The goal of this study was to determine various feature vectors of foot pressure and gait parameters of patients with stroke through the use of a wearable sensor and to compare the gait parameters with those of healthy elderly people. To monitor the participants at all times, we used a simple measuring device rather than a medical device. We measured gait data of 220 healthy people older than 65 years of age and of 63 elderly patients who had experienced stroke less than 6 months earlier. The center of pressure and the acceleration during standing and gait-related tasks were recorded by a wearable insole sensor worn by the participants. Both the average acceleration and the maximum acceleration were significantly higher in the healthy participants ($p < .01$) than in the patients with stroke. Thus gait parameters are helpful for determining whether they are patients with stroke or normal elderly people.

Key words: Gait Analysis, Health Monitoring System, Post-Stroke, Wearable Sensors

1. Introduction

The World Health Organization (WHO) defines stroke as a stroke is caused by the interruption of the blood supply to the brain, usually because a blood vessel bursts or is blocked by a clot. This cuts off the supply of oxygen and nutrients, causing damage to the brain tissue. Strokes are classified as ischemic stroke which caused by inadequate supply of oxygen and nutrients in the blood after cerebrovascular blockage, and Hemorrhagic stroke which caused by hematoma caused by cerebral vascular injury. Risk factors of stroke onset are known to be related to hypertension, diabetes, obesity, dyslipidemia, etc. The Stroke Association recom
mends that it is important to identify and track pathophysiologic risk factors with appropriate diagnostic tests for recurrence and secondary prevention of stroke. However, according to the Global Burden of Disease (GBD) survey, the mortality rate of stroke among the elderly over 70 years old was 7.76% in USA, 6.99% in Germany, 9.47% in Japan and 13.02% in Korea (GBD, 2017). It is difficult to directly compare the difference in race, culture, economic level and medical level according to the region, but in Korea, the mortality rate due to stroke is significantly higher than in other countries. Symptoms and the severity after stroke are determined by the position of the brain lesion and the size of the lesion, but it is most important to treat the specialist immediately after the onset. Furthermore, due to this, the timing of appropriate treatment is missed, increasing the patient’s mortality rate and the rate of disability. The typical clinical features of stroke include hemiplegia, disturbance of sense, spasticity, incoordination, cognitive impairment, apraxia, hemineglect, and dysphagia. In the early stages of stroke, muscle weakness and decreased muscle tension lead to paralysis. Among them, hemiplegia due to neurological disorders is very common in more than 80% of stroke patients in general (Duncan et al., 2015). The weakening of neurological muscular strength makes it difficult for stroke patients to maintain the center of the body in a static standing situation or to make normal walking (Duncan et al., 2015; Wevers et al., 2009). The movement of the pressure center (center of pressure, CoP) of the body in the static standing posture is being used as an evaluation tool to diagnose the balance disorder (Bohannon, 1997). Gollhofer (1989) and Horstmann (1990) reported that the trajectory of the center of gravity (COG) gives information on the control of the movements of the body necessary to maintain a standing posture. While the trajectory of difference of the center of pressure from the center of gravity (COP-COG) presents the neuromuscular stiffness of the biomechanical system controlling the center of gravity. Moreover, Foot Pressure is and index to evaluate the parameter of balance and walking. It may cause musculoskeletal damage as well as physiological disorders when foot pressure exceeds the normal range (Yang et al., 2015).

Articulation in walking after a stroke involves a cooperative pattern of lower limbs rather than selective movement (Chen et al., 2005). Then, it adapts to a safer and more stable walking pattern in order to magnify the decrease of sensory information from the foot (Yang et al., 2005). Insufficient single-leg support or uncontrolled forward movement is considered a fundamental dysfunction leading to asymmetry. Asymmetry consists of a decrease in stance period time and extension of swing leg period (Peter & Arthur, 2005). Both leg support periods and stance periods are longer than normal on both legs (Bohannon, 1986; Bohannon, 1987; Bohannon, 1991; Bohannon, 1997; Brandstater et al., 1983; Nadeau et al., 1999; Nakamura et al., 1998). Such asymmetry leads to an increase in energy costs, falls, joint abnormalities, burden on joints, and pain (Morris et al., 1986; Olney, 1969). Methods for measuring such asymmetry are described in various documents. The expression for obtaining temporal asymmetry is calculated by dividing the value obtained at the paralyzed side swing period / paralyzed side stance period by the non-paralyzed side swing period / non paralyzed side stance period time (Olney, 1969; Patterson et al., 2010). The asymmetry of the single-leg support time is obtained by 1-single-leg support time (paralyzed side) / single leg support time (non-paralyzed side). The stride ratio is calculated by dividing the stride (meters) on the paralyzed side by the non-paralyzed side stride (meters) (Balasubramanian et al., 2007). The larger these values, the more notable the asymmetry is (Hsu, 2003). In stroke patients, the walking speed generally decreases. In a healthy subject, the comfortable walking speed is about 1.3 m/s (Bohannon...
et al., 1997), and in a hemiplegic patient, the average walking speed is set to 0.23 - 0.73 m/s (Olney & Richards, 1996). Perry is classified into three according to walking speed, and when it is less than 0.4 m / s it is restricted to indoor movement, some restriction occurs outdoors at 0.4 to 0.8 m / s, outdoor movement is not restricted at 0.8 m / s or more It revealed that (Perry, 1995).

According to the results of previous studies, body balance and walking characteristics are obvious obstacles caused by stroke. As mentioned above, quantitative evaluation methods by the nervous system damage after stroke onset can be measured, there aren’t any systems monitoring and detecting the stroke features when they are standing up and walking. In other words, the delay in detection of a sympathetic postponed the treatment time of the stroke patients, thus causing a fatal disorder or affecting the maintenance of life.

Nevertheless, elder people have been still exposed to the high risk of stroke should be monitored during their daily activities and also the sensors and the decision making algorithms to detect their stroke symptoms are needed. At that reason, in this study, the difference in walking and standing characteristics between normal elderly and stroke patients is defined as a feature vectors. And also, these results will be used as a feature of the algorithm development that will be applied to the stroke monitoring system during the walk.

2. Methods

All experimental procedures were carried out after approval of the institutional review board (KRISS-IRB-2017-07).

2.1. Stroke Monitoring System

Our elderly health (stroke) monitoring system was designed and suggested as shown in the Fig. 1 (Park et al., 2017). Hyper-connected self-machine learning engine controls the system. The elements of the system are a knowledge base, big data, network security, real-time data monitoring using wearables, and self-learning engine. The knowledge base would have risk factors, medical health records, psycho-logical factors, gait
and motion patterns, and bio-signals. The old peoples’ activities, physiological, and bio signals are monitored in real-time through wearable sensors. The self-machine learning engine would include multi-model learning (SVM, Bayes, RF, CNN, LSTM, deep learning) and model generator. If the proposed system predicts stroke symptom above 90%, it will generate an alarm to family, the victim, people around the victim, and healthcare professionals. Then the victim will get the timely medical assistance. The Stroke Monitoring System using gait parameters such as, insole foot pressure and accelerometer, is proposed. Gait patterns such as gait speed, foot pressure etc. of normal person and stroke patient are significantly different from each other. Wearable IoT (Internet of Things) devices and statistical technique are able to detect stroke onset of elderly adults. Entire system will feed subject’s physiological data to cloud engine to compare real-time data and reference data in order to detect stroke during gait activities.

2.2. Subjects

220 normal elderly people over 65 years old and 63 elderly patients who were less than 6 months after the onset of stroke participated in this study as in the Table 1. Study was performed in A National University Hospital, Daejeon, South Korea. Healthy participants were recruited to the elderly enrolled at the local silver center, and patients were recruited for the elderly who were in hospital or after rehabilitation. The stroke patients were limited to those who could walk more than 30m independently without a walking frame. All participants performed basic physical examinations (height, weight, electrocardiogram, blood pressure, blood test) before the experiment, and participants were paid participation fee including transportation expenses. In addition, the participants were instructed to give up the experiment at any time according to the health condition of the experiment day. Proposed Gait monitoring system is consists of insole foot Pressure sensor and accelerometer which will be attached to foot as shoe insole for gathering gait speed, foot pressure and other gait signals.
Table 1. Demographic characteristics of recruited elderly normal and stroke patients

<table>
<thead>
<tr>
<th></th>
<th>Normal elderly (n=220)</th>
<th>Elderly Stroke Patients (n=63)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender (Years)</td>
<td>M: 98 (44.5%)</td>
<td>M: 42 (66.7%)</td>
</tr>
<tr>
<td></td>
<td>F: 122 (55.5%)</td>
<td>F: 21 (33.3%)</td>
</tr>
<tr>
<td>Age (Mean, std.)</td>
<td>68.45 ± 4.22</td>
<td>73.26 ± 6.18</td>
</tr>
<tr>
<td>Height/Weight (cm)</td>
<td>157.13/59.76</td>
<td>157.47/60.19</td>
</tr>
<tr>
<td>Systolic /Diastolic Blood pressure (mmHg)</td>
<td>134.22/79.33</td>
<td>134.78/79.55</td>
</tr>
</tbody>
</table>

2.3. Data acquisition system

The insole sensor was the Dynamic pressure mapping system, Dynafoot 2 (TechnoConcept, Pitaugier, MANE, France). There are 58 pressure (resistance) sensors and accelerometers on the bottom of the insoles. The thickness of the insole is 2mm and the size of the resistance sensor is 9 * 9mm and the measurement range is 2000g. The accelerometer was twin-axial and the measuring range was +/- 6g. The sampling rate was 100Hz. And the data transfer module is 49 * 38 * 19mm which is mounted on the shoe.

In the recording mode, there is no limit to the measuring distance and it is possible to measure up to 3.5 hours.

2.4. Data analysis

Experimental data was measured using Dynafoot 2 and extracted using Dynafoot2_V2.2.14.0 software. The measured features were the pressure per cell, the center of pressure [CoP, CoP_Left_x axis (medial, lateral), CoP_Left_y axis (anterior, posterior), CoP_Right_x axis (medial, lateral), CoP_Right_y axis (anterior, posterior)], the acceleration (Acc._left foot, acc._right foot,), and the ground reaction force (GFR, GFR._left foot, GFR._ right foot.).

Gait data were analyzed using IBM SPSS Modeler 18.0. After data preprocessing (outlier removal), patient data were amplified to adjust the data distribution ratio of stroke patients and normal persons. Then statistical analysis method was paired t-test at a confidence level of 95%.

3. Results

3.1. Static Standing Position

3.1.1. Plantar Center of Pressure (CoP)

CoP displacement was measured in both feet of a normal elderly person and a stroke patient in a static standing state, and was analyzed into the medial, lateral, anterior, and posterior regions (confidence level of 95%) as shown Fig. 3.

3.2. Gait/Movement

3.2.1. Gait task duration

After standing in static condition, participants performed 20m gaiting test along the guide tape line. Fig. 4 shows the gaiting time of the normal group and the patient group. The normal group reached the end point with 18.98 ± 4.672s, while the patient group reached the end point with 43.75 ± 29.830s. There was a significant difference in arrival time between two groups (p-value <.01).

3.2.2. Gait accelerations

The maximum and average accelerations of the feet were measured from the accelerometer embedded in the insole, and paired t-test was performed. In the Fig. 5, the average acceleration of the normal group was measured as 17.18 ± 10.563m/s² and 19.44 ± 19.365m/s², left foot and right foot respectively, and the average acceleration of the patient group was measured as 12.20 ± 1.167m/s² and 12.67 ± 1.519m/s². It was clear that
Fig. 3. CoP displacement from plantar center of normal group and stroke patients group: (a) medial and lateral CoP displacement of left plantar, (b) anterior and posterior CoP displacement of left plantar, (c) medial and lateral CoP displacement of right plantar, (d) anterior and posterior CoP displacement of right plantar (** p-value <.01).

Fig. 4. Gait duration from the starting point to the end point (** p-value <.01).

Fig. 5. Acceleration of the normal group and the stroke patient group during gating: (a) average acceleration, (b) maximum acceleration (** p-value <.01).
the average acceleration of the normal group was significantly higher than the average acceleration of the patient group. The maximum acceleration of the normal group was 75.24 ± 9.758m/s² and 73.39 ± 11.700m/s², left foot and right foot respectively. The maximum acceleration of the normal group was 66.96 ± 11.597m/s² and 69.28 ± 11.563m/s², respectively. Both the average acceleration and the maximum acceleration were significantly higher in the normal group ($p$-value <.01).

4. Discussion

The CoP displacement in the left foot of the stroke patients was significantly larger than that of the normal elderly. The anterior and posterior CoP displacement showed a significant increase in stroke patients also. Especially the anterior movement was very prominent. It was also found that in the stroke patients, the CoP of the left foot was shifting in the anterior-medial direction. On the other hand, in CoP displacement of the right foot, the shift value in the anterior-posterior direction was larger in patients with stroke. These results suggest that stroke patients have difficulty in controlling the balance because they cannot tolerate weight bearing on the plantar part. Haart et al. (2004) reported that stroke patients had weight gain in the forefoot due to an ankle muscle imbalance and that the balance was shaken to the outside of the foot. It obvious to maintain balance in the anterior medial side to control the unbalance in the stroke patients. Therefore, when the patient was standing in a static state, it was confirmed that the stroke patient maintained an anterolateral balance and that the CoP of the plantar in the anteroposterior direction were higher.

The CoP from normal and patient groups were also plotted and the normal range of pressure center values was specified. The range of the normal that does not include outliers was indicated by box in the scatter plot as shown in the Fig 6. In the left foot, patient data of the anterior-lateral side and normal group data of the posterior-lateral side were distributed. On the right foot, the patient data of the posterior side were distributed and the data of the normal side were scattered on the mediolateral part. As a result, CoP values outside the normal range were also observed in the normal group. This suggests that physical degeneration due to aging has generated an abnormal value even though it is a normal elderly person.

Fig. 6. CoP distribution of normal elderly people and stroke patient (left and right foot, respectively)
In addition, gait time and acceleration were obtained from the gait test. The results showed that the gait time of the normal group was significantly faster and the acceleration value was higher in the normal group. From these results, it was clear that walking speed was a very clear feature in predicting stroke. As shown in Fig. 7, it was confirmed that the acceleration of patients who have plotted the left and right maximum acceleration values on a three-dimensional graph was clearly distinguished from the range of normal persons.

![Fig. 7. CoP placement limit box of normal elderly people (left and right foot, respectively)](image)

However, since the shape of the foot is very different according to the user, and the state of the surface of the ground is different according to the environment in which the user lives and the user, it is difficult to detect the abnormal data only through the simple statistics. Therefore, in the future, the conditions for the experimental environment will be expanded, bio-signal data will be collected, and reliability will be improved by using algorithms using machine learning and deep learning.

5. Conclusions

Balance in standing posture and gait in patients with stroke are important factors in evaluating functional independence (Turnbull, Charteris, & Wall, 1995). And those have been analyzed in various methodologies. Balancing in standing has been evaluated using the COP, the COP-COG, and the Foot pressure. Hence, the evaluation tools of the gait are much more diversified. The common methods for hemiplegic are the velocity, the cadence, the step length, the single time ratio, and the stance phase symmetry ratio. Among these, the velocity is easy to measure and corresponds to the clinical condition of the patient (Wall & Turnbull, 1986; Roth et al., 1997). Also, it was observed that hemiplegic patients were closely related to the cadence, the velocity, the muscle strength, the Barthel index score and the gait pattern (Dettman, Linder, & Sepic, 1987). On the other hand, the most prominent gait patterns for stroke patients presented the low gait velocity, the short stance phase, and the difference in step length between the paralyzed side and non-paralyzed side of the body (Mauritz, 2002). As such, it has been developed into a multi-faceted evaluation method such as the COP, COG and foot pressure method when standing and the velocity, the cadence, the step length, the single time ratio, and the stance phase symmetry ratio method when walking. For real-time health monitoring, the temporal and spatial variables during daily time must be measured accurately. In addition, there should be no limitation in the measurement environment in order to determine the difficulty of maintaining the balance of the body and the abnormality of walking. However, foot pressure varies considerably depending on the road surface, and gyro sensors using magnetic sensors are affected by such values in environments with many electronic devices. Therefore, sensors and measurement variables for daily monitoring should not be influenced by the environment, and the use of optimal parameters should be a priority.

The purpose of this study was to extract the optimal variables to detect abnormalities of stationary posture and walking during daily life, and to find the difference
between stroke patients and the normal elderly. However, the stroke patients who were in-rolled in this study were patients within three months of onset and were unable to collect patient data at the time of onset. However, we will develop machine learning and deep learning algorithms and embed them in our stroke monitoring system. After that, we will conduct follow-up studies on older people to monitor stroke incidence and will also collect additional data at the time of onset. Once the system has been developed and validated, it is expected to reduce the sequelae and mortality caused by delays in treatment time after stroke.

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Institute for Health Metrics and Evaluation (IHME), GBD Compare, Viz Hub (https://vizhub.healthdata.org/gbd-compare/).


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