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Analysis for the Gait Patterns of Healthy Subjects During March

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Abstract

Walking is one of the most fundamental and important activities of human that is strongly connected with human health, and there has already been many researches on the human gait. However, these studies mainly investigate the gait patterns related to some specific injuries or diseases, and there is few studies on the gait of healthy people. We thus in this study tried to analyze the gait patterns of healthy subjects, and to establish some criteria for estimating the walking ability of the healthy subjects. To reach these goals, we performed our experiment using 66 students from National Defense Academy of Japan who perform their daily training for march, namely, controlled walking. The gait patterns from the students were integratively analyzed by using cluster analysis and principal component analysis, and as a result, we succeeded to classify the walking abilities of the subjects.

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Keyword: :Gait Analysis; Functional evaluation for normal subjects; Acceleration sensor; March, Statistical analysis

1. Introduction

Walking is the very fundamental activity of human, and there has already been many studies on the human gait. However, many of the studies focus on the specific gait patterns related to some specific injuries, strains or diseases. For example, the particular walking pattern of Parkinson's disease patient is investigated in terms of the corresponding symptoms of the disease [1-3]. In the other examples, the gait patterns derived from bowleg [4], knock-knee [4], and flatfoot [5] are also studied. The gait patterns derived from the symptoms are clear objects of the investigation and they are in a sense easily distinguished targets. On the contrary, the evaluation for the sound

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gait patterns contains some difficulties, because even if a walker has unimpaired walking ability, his or her walking includes many patterns those are at least seemingly neutral. In other words, it is difficult to find out the good and bad pattern from the gait patterns of the healthy walker. This may be why there are not so many studies on the gait of healthy people.

We thus set our goals in this study as follows:

- To establish some criteria for the evaluation of gait patterns from healthy subjects.
- To develop a method for the detection of a slight defectiveness in seemingly sound walking that are not detected by a usual diagnosis.
- To develop a method of training to improve the walking ability.

To accomplish these goals, we chose the students from National Defense Academy of Japan (they are referred to as NDA student in the following text) as subjects, and chose the military march as a walking task. March is an important activity for the members of military forces and cadet schools, and they are requested to improve their walking ability to make their parade more regular, orderly and systematic. Of course this is the case with NDA students, and actually they have daily training of march twice a day. Therefore, by choosing the NDA students as subjects, we easily got many subjects of our experiment those vary in their training period by year.

Additionally, we set the following subgoals:

- To establish an easy method for the measurement of gait patterns without any extensive equipment. This is intended for the convenience in the future clinical applications.
- To establish a method for the simultaneous measurement of multiple subjects. This is intended for the future study of group walking by people in an alignment.

Therefore we developed a method for the measurement and analysis of human gait using a single acceleration sensor.

2. Experiment

2.1. Settings for walking task and measurement

As mentioned above, the task in this study is march walking: the subject NDA student was directed to walk to about 110 bpm music (Imperial Japanese Army March) through about 100 m pavement swinging his arms as he does in daily march training. The subject was equipped with a single acceleration sensor in his trunk of the body, directly above the center of the superior part of sacral bone (Fig. 1a). The sensor used in this experiment was WAA-006 from ATR-Promotions, Japan. This sensor is capable of measuring triaxial acceleration and angular velocity at the intervals of 3 msec, and sending the sampled data via Bluetooth.

In the actual setting during the experiment, the sampling rate of the sensor was set to be 200 Hz, namely, the intervals of the sampling were 5 msec. The sampled data were transmitted to the PC wirelessly, and the data at the beginning 10 sec and at the last 10 sec were removed and were not analyzed. From the viewpoint of the subject, the

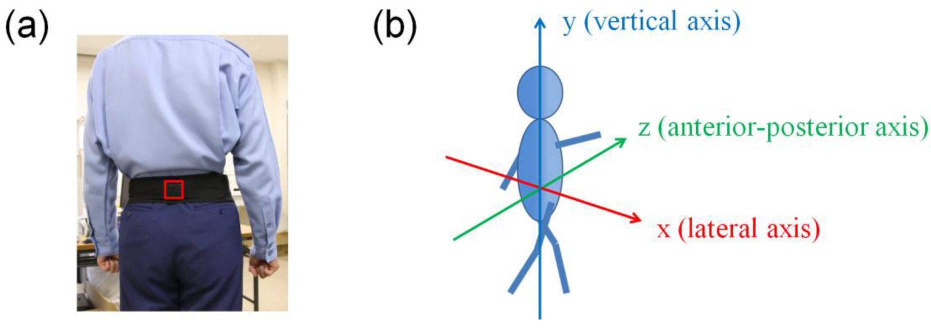

Fig. 1. (a) The acceleration sensor wore by a subject. The sensor was fixed using a band, and the red rectangle in the figure indicates the position and the size of the sensor. (b) A schema for the setting of 3 axes.

lateral axis is designated x-axis, the vertical axis is designated y-axis, and the anterior-posterior axis is designated z-axis (Fig. 1b).

From the data of triaxial acceleration and angular velocity, the displacement of the subject body and the angular displacement around 3 axes were calculated. The method is based on Kobayashi et al. [6]. For example, the displacement in x-axis is calculated in the following manner. First, to obtain the x-axial velocity V_x, the time integral of the x-axial acceleration A_x is calculated.

$$V_x(t) = \int_0^t A_x(t)dt \tag{1}$$

Since this integration contains some errors derived from the effect of gravity and so on, the offset component is removed by subtracting the average velocity from 1 sec before and after each time point.

$$V_x'(t) = V_x(t) - \overline{V_x(t)} = \int_0^t A_x(t)dt - \frac{1}{2}\int_{t-1}^{t+1} V_x(t)dt \tag{2}$$

In the same way, the displacement x is calculated from velocity V_x.

$$X(t) = \int_0^t V_x'(t)dt \tag{3}$$

$$X'(t) = X(t) - \overline{X(t)} = \int_0^t V_x(t)dt - \frac{1}{2}\int_{t-1}^{t+1} X(t)dt \tag{4}$$

Angular displacement θ_x is also calculated from angular velocity ω_x, with a single integration.

$$\theta_x(t) = \int_0^t \omega_x(t)dt \tag{5}$$

$$\theta_x'(t) = \theta_x(t) - \overline{\theta_x(t)} = \int_0^t \omega_x(t)dt - \frac{1}{2}\int_{t-1}^{t+1} \theta_x(t)dt \tag{6}$$

Since the displacement in x, y-axes and the angular displacement in x, y, z-axes are cyclic, the subtraction of the offset component in (2), (4), (6) are possible. According to Kobayashi et al., the error from this calculation is at most about 5 % [6]. Fig. 2 illustrates an example of the trunk trajectory of a subject that was calculated by using the method above.

The intervals of the strides were calculated based on the displacement in y-axis (vertical axis). During walking, when the swinging leg touch the ground, the both legs are maximally opened to anterior-posterior direction and the position of the trunk gets minimal. Therefore, the stride can be calculated based on the minimal points of the displacement in y-axis.

In the experiment, 66 NDA students were used as subjects. They consisted of 15 students in the first grade, 10 students in the second grade, 19 students in the third grade, 10 students in the fourth grade, and 12 students in the third or the fourth grade who belong to the honor guard (the honor guard members are specially trained to perform ceremonial presentation, and they are expected to have high performance in walking task). The subjects were from 18 to 23 years old, and in this study, they were all male.

2.2. Settings for walking task and measurement

Using the experimental data from 66 NDA students, we analyzed the 8 factors listed in Table 1, and the result is illustrated in Fig. 3. However, contrary to our expectation, no factor showed the correlation with the grade or belonging of the subjects. We thus in the next step performed cluster analysis and principal component analysis on the experimental data from 66 NDA students to integratively evaluate the walking ability of the subjects.

3. Statistical analyses

As mentioned in the previous chapter, any single factor in Table 1 does not correlate with the attributes of the NDA students. Therefore we performed cluster analysis and principal component analysis using the 8 dimensional data obtained from 66 NDA students, to analyze the data integratively.

Fig. 4 illustrates the result from the cluster analysis. From this result, the 66 NDA students were classified into 7 groups. Furthermore, Table 2 exhibits the profiles of the principal components as a result of the principal component analysis.

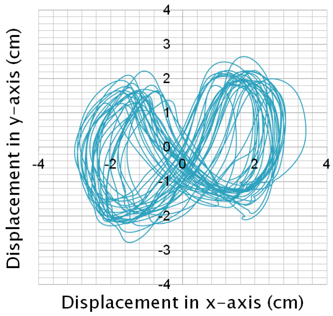

Fig. 2. An example of the trunk trajectory of a subject.

Table 1. The factors analyzed based on the experimental data. In the table, $X(t)$, $Y(t)$, S, $\theta_x(t)$, $\theta_y(t)$ and $\theta_z(t)$ mean displacement in x-axis, displacement in y-axis, interval of the strides, angular displacement around x-axis, angular displacement around y-axis and angular displacement around z-axis, respectively.

Items for the analysis	Formal expression
1. Time-averaged time integration on the absolute values of the displacement in x-axis	$\int_0^t \lvert X(t) \rvert dt / t$
2. Time-averaged time integration on the absolute values of the displacement in y-axis	$\int_0^t \lvert Y(t) \rvert dt / t$
3. Time-averaged time integration on the root-mean-square of the displacements in x-axis and y-axis	$\int_0^t \sqrt{X(t)^2 + Y(t)^2} dt / t$
4. Variance of the intervals of strides	$\frac{1}{n}\sum_{i=0}^{n}(\bar{S} - S_i)^2$
5. Absolute value of the deference in the average stride interval between left and right legs	$\lvert \overline{S_{left}} - \overline{S_{right}} \rvert$
6. Time-averaged time integration on the absolute values of the angular displacement around x-axis	$\int_0^t \lvert \theta_x(t) \rvert dt / t$
7. Time-averaged time integration on the absolute values of the angular displacement around y-axis	$\int_0^t \lvert \theta_y(t) \rvert dt / t$
8. Time-averaged time integration on the absolute values of the angular displacement around z-axis	$\int_0^t \lvert \theta_z(t) \rvert dt / t$

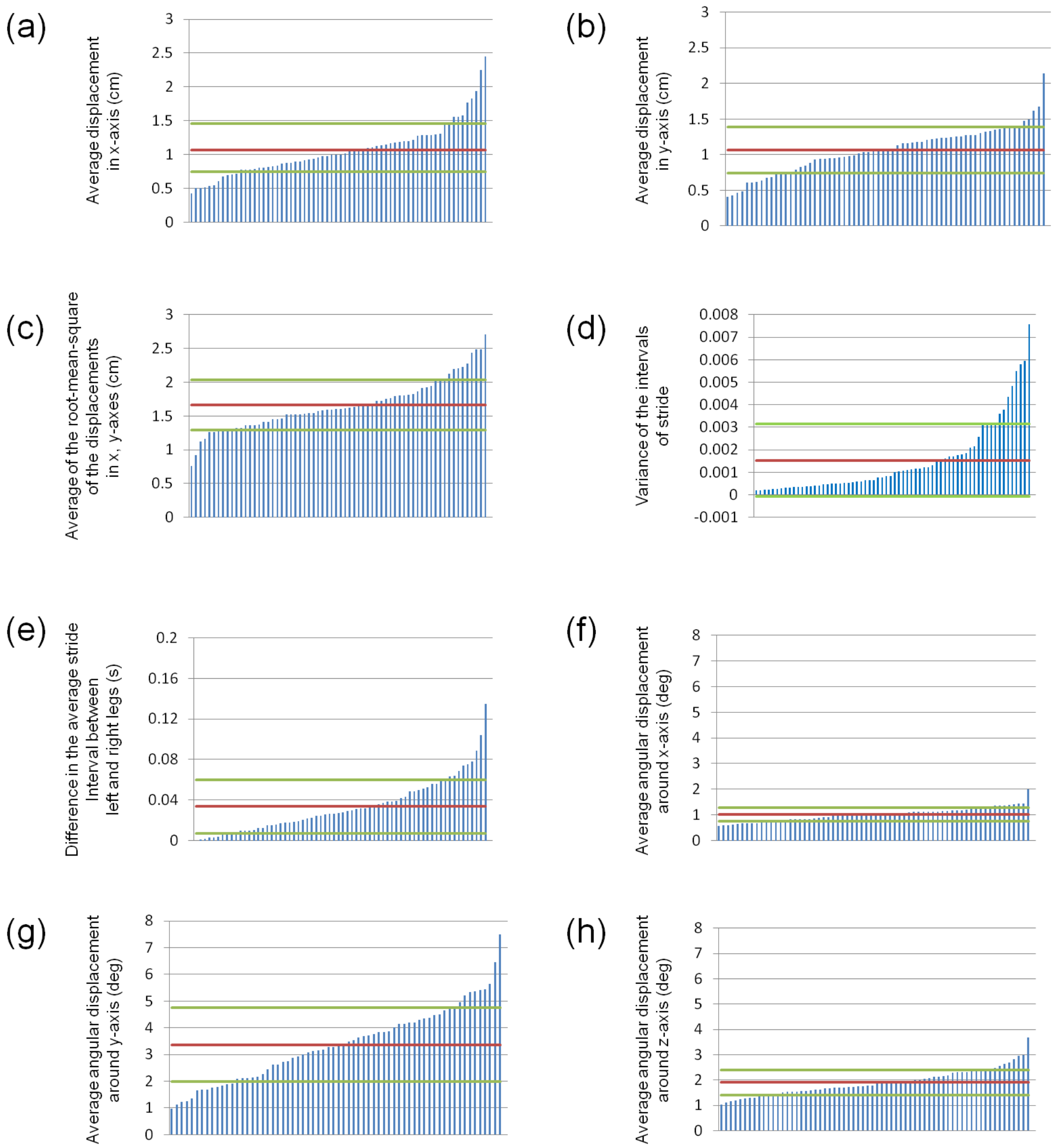

Fig. 3. The results from the analysis on 8 factors listed in Table 1. The data from the 66 NDA students are arranged in an ascending order. The red line in each graph indicates the average value and the green lines indicate the average plus or minus standard deviation. (a) Time-averaged time integration on the absolute values of the displacement in x-axis. (b) Time-averaged time integration on the absolute values of the displacement in y-axis. (c) Time-averaged time integration on the root-mean-square of the displacements in x-axis and y-axis. (d) Variance of the intervals of strides. (e) Absolute value of the deference in the average stride interval between left and right legs. (f) Time-averaged time integration on the absolute values of the angular displacement around x-axis. (g) Time-averaged time integration on the absolute values of the angular displacement around y-axis. (h) Time-averaged time integration on the absolute values of the angular displacement around z-axis.

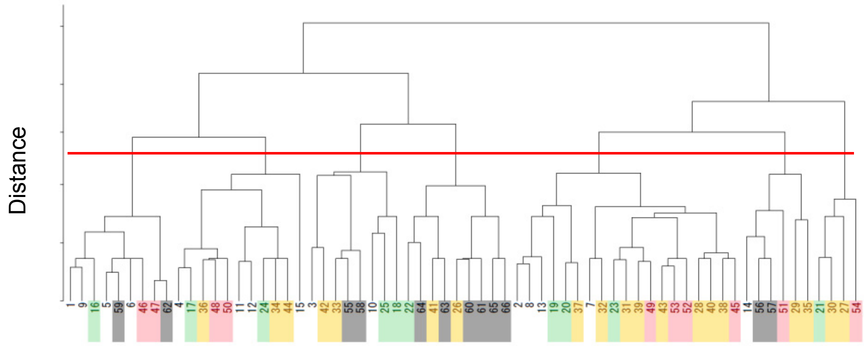

Fig. 4. The result of cluster analysis on the data from 66 NDA students. Ward's method was used for the clustering. The vertical axis indicates the distance between clusters. The subjects are indicated by numbers, and the white, green, yellow, pink and grey colors on the numbers indicate 1st grade, 2nd grade, 3rd grade, 4th grade and honor guard, respectively.

Table 2. The profiles of the principal components. The values in the largest cell indicate the principal component scores.

	Principal Components							
	1st	2nd	3rd	4th	5th	6th	7th	8th
1. Time−averaged time integration on the absolute values of the displacement in x−axis	0.262	0.573	0.149	−0.426	0.087	0.433	0.015	0.451
2. Time−averaged time integration on the absolute values of the displacement in y−axis	0.554	−0.227	0.158	0.327	−0.226	−0.311	−0.185	0.572
3. Time−averaged time integration on the root− mean−square of the displacements in x−axis and y−axis	0.629	0.191	0.231	0.006	−0.134	0.039	−0.162	−0.685
4. Variance of the intervals of strides	−0.333	−0.198	0.567	0.060	−0.063	0.349	−0.632	0.012
5. Absolute value of the deference in the average stride interval between left and right legs	−0.141	−0.014	0.721	−0.162	−0.169	−0.279	0.573	−0.010
6. Time−averaged time integration on the absolute values of the angular displacement around x−axis	0.278	−0.519	0.100	0.148	0.461	0.526	0.364	−0.001
7. Time−averaged time integration on the absolute values of the angular displacement around y−axis	−0.062	0.412	0.218	0.445	0.701	−0.285	−0.085	0.003
8. Time−averaged time integration on the absolute values of the angular displacement around z−axis	0.133	−0.325	0.028	−0.679	0.431	−0.396	−0.269	−0.009
Eigenvector	2.128	1.543	1.350	1.154	0.792	0.534	0.495	0.004
Contribution ratio	0.266	0.193	0.169	0.144	0.099	0.067	0.062	0.000
Cumulative contribution ratio	0.266	0.459	0.628	0.772	0.871	0.938	1.000	1.000

The first three principal components were used in our analysis as will be shown later, though the cumulative contribution rate is 0.628 at the third principal component and this is a bit low (Table 2). However, as indicated later, this was sufficient for our analysis. The correlationship between the analyzed factors and the factors belonging the principal components are indicated in Fig. 5. Furthermore, the integrative analysis using the cluster analysis and principal component analysis is shown in Fig. 6. The last result indicated that by combining the statistical analyses, the walking ability of the subjects were classified and evaluated.

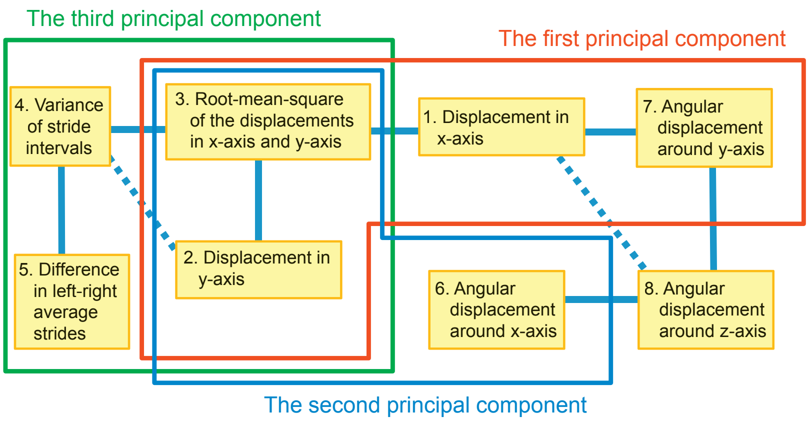

Fig. 5. The correlationship between the analyzed factors and the memberships of each principal component clarified as the result of the principal component analysis. The factors those showed correlationship at 5 % significance level are connected with blue lines, and the factors those has marginally significant correlationship whose p-value is less than 0.1 are connected with dashed blue lines. The factors those have more than about 0.2 principal component score in one component are regarded as the member of that principal component. In the figure, the members of the first principal component are enclosed with the red lines, the second with the blue lines, and the third with the green lines.

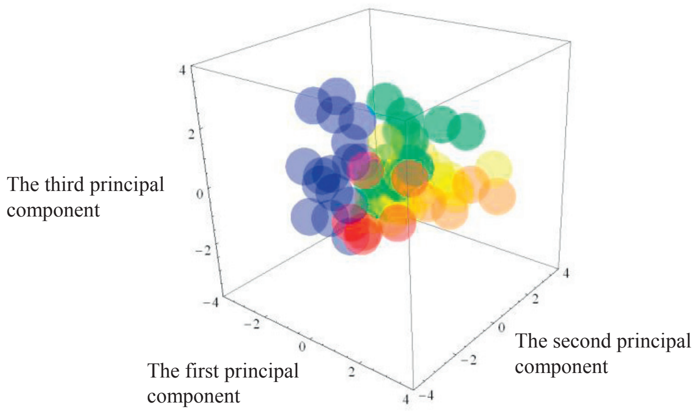

Fig. 6. The integrated result from the cluster analysis and principal component analysis. Each plot represents the data from one subject, and the color of the plot indicates the cluster to which the subject belongs.

4. Discussion

In this study, we tried to establish some criteria for the evaluation of walking function of the healthy subjects. We performed an experiment using 66 NDA students and analyzed the gait patterns of them. Eight factors were chosen as the indicators of the gait pattern. Actually, the 8 factors were almost everything that can be easily measured using a single sensor, however, any single factor showed correlation with the attributes of the subjects. We then tried to integratively analyze the gait patterns from the experiment, and performed some statistical analyses.

The cluster analysis and the principal component analysis gave the consistent results, as shown in Fig. 6. The members of the clusters from the former analysis were closely located in the 3 dimensional space of the principal components. Furthermore, the data in Fig. 6 enable us to evaluate and classify the walking ability of the subject.

In the 3 dimensional space illustrated in Fig. 6, there are 3 axes: they are first to third principal components, and the lower values in each component indicates the higher stability in walking. The factors 1-3, 7 are regarded as the members of the first principal component, the factors 2, 3, 6 are of the second, and the factors 2-5 are of the third. In every factor the higher value indicates the higher degree of displacement and the higher degree of fluctuation in the rhythm, as is indicated by the definitions of the factors in Table 2. From this viewpoint, we can evaluate the functionality of the classified clusters. For example, the orange cluster in Fig. 6 has high values in all of the 3 principal components, and thus the cluster is evaluated as a low functionality group. The yellow and green clusters have medium values in every principal component, thus they are estimated as medium and normal functionality groups, and the indigo cluster has low values in every axis, thus they are regarded as a high functionality group.

We believe that, here, it is not so important to investigate the details of the characteristics of every cluster in Fig. 6. What important here is that we got a criterion to evaluate and classify the functionality of walkers, and now we are able to observe how a subject transits in the space consists of the principal components. Thus in the future study, we will make an investigation on what kind of change can be induced within a patient or healthy subject along with some training, rehabilitation or remedy and such change will be detected by using the proposed method.

References

1. Stolze H, Kuhtz-Buschbeck JP, Drücke H, Jöhnk K, Illert M, Deuschl G. Comparative analysis of the gait disorder of normal pressure hydrocephalus and Parkinson's disease. *J. Neurol. Neurosurg. Psychiatry* 2001;**70**:289-97.
2. Hausdorff JM. Gait dynamics in Parkinson's disease: Common and distinct behavior among stride length, gait variability, and fractal-like scaling. *Chaos* 2009;**19**:026113.
3. Hove MJ, Suzuki K, Uchitomi H, Orimo S, Miyake Y. Interactive rhythmic auditory simulation reinstates natural 1/f timing in gait of Parkinson's patient. *Plos One* 2012;**7**:e32600.
4. Sharrard WJW. Knock knees and bow legs. *Brit. Med. J.* 1976; **1**:826-7.
5. Leung AKL, Mak AFT, Evans JH. Biomechanical gait evaluation of the immediate effect of orthotic treatment for flexible flat foot. *Prosthet. Orthot. Int*. 1998;**22**:25-34.
6. Kobayashi T, Miyake Y, Wada Y, Matsubara M. Kinematic analysis system of walking by acceleration sensor: An estimation of Walk-Mate in post-operation rehabilitation of hip-joint disease. *Trans. SICE* 2005;**42**:567-76.