Quantitative Assessment of Fall-Limping by Acceleration Analysis Using Singular Value Decomposition

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Abstract. It is important to accurately assess walking ability in walking rehabilitation to track the process of recovery and design proper rehabilitation program for the patient. A quantitative walking ability assessment method is proposed based on acceleration analysis using singular value decomposition (SVD) in this study. The 3-dimentional acceleration during walking is measured by wearable wireless accelerometers. Singular value decomposition is used to acquire walking patterns from the time-series acceleration data. We conducted a fall-limping experiment to verify the usefulness of the proposed method. Two levels of fall-limping are simulated in the experiment by differentiating the lengths of the legs. The accelerations of the middle of shank, the back of the waist and the back of the neck are measured and analyzed. The results showed that the first singular values inferred from the acceleration data of the shank and the neck in the right-left direction were significantly different according the level. This was due to the swing caused by the leg length difference. The waist was kept stable might be because of the important role it played in keeping balance since the center of the body is in the waist. These results suggest that the acceleration analysis using SVD might be a useful tool in quantitative assessment of walking ability.

Keywords: Walking Rehabilitation, Fall-Limping, Singular Value Decomposition (SVD), Acceleration Analysis.

1. INTRODUCTION

Walking rehabilitation for those with walking disabilities to recover walking ability is very important sin the people suffering from walking impairments due to illness or accident are increasing in an aging society with a low birth rate in countries like Japan. We are developing omnidirectional walkers, which can move in any direction while maintaining its orientation, for standing exercise [1] and sitting exercise [2], shown in Fig. 1(a) and Fig. 1(b) respectively. Walking is a complex combination of motions, which includes not only forward and backward motions, but also right and left motions, oblique motions, rotations and so on. Therefore, with the omnidirectional movement of the walkers, diverse motion groups can be carried out in walking rehabilitation, thus to obtain an early recovery. The walker for walking exercise is designed for those able to keep standing posture by themselves, and the walker for seated exercise is designed for severe patients not able to stand. The effect for early recovery of walking disabilities of omnidirectional walking exercise has been proved in clinical test [3].

(a) For walking exercise (b)For seated exercise

Fig. 1. Omni-directional walkers.

During the process of walking rehabilitation, walking ability assessment is important to track the recovery and design the proper rehabilitation program according to the condition of the patient. Clinical measurement of walking ability are mainly based on inspection of the physical therapist, sometimes with the help of muscle strength measurement, X-ray examination, ground reaction force, 3D motion analysis, acceleration analysis, gait and stride analysis, or electromyography (EMG) and so on. Objective measurements and correct interpretation of the measurement results can have a substantial impact on the recovery. Furthermore, a convenient assessment method is desired for those who rehabilitate and exercise at their homes, thus they can know their status anytime by themselves. In this study, we propose a walking ability assessment method based on acceleration analysis using singular value decomposition (SVD). Our purpose is to develop a method both reliable for clinical measurement and convenient for the patients to use by themselves in everyday life.

The remainder of this paper is organized as follows. In Section 2, we describe the experiment to measure the acceleration during walking. Two levels of fall-limping are simulated in the experiment by differentiating the lengths of the legs. Acceleration analysis based on SVD is proposed in Section 3. Section 4 presents the experiment results and discussions that justify the use of SVD. In Section 5, we conclude the paper and discuss possible future research directions of walking ability assessment.

2. Acceleration Measurement with Wearable Wireless Accelerometers

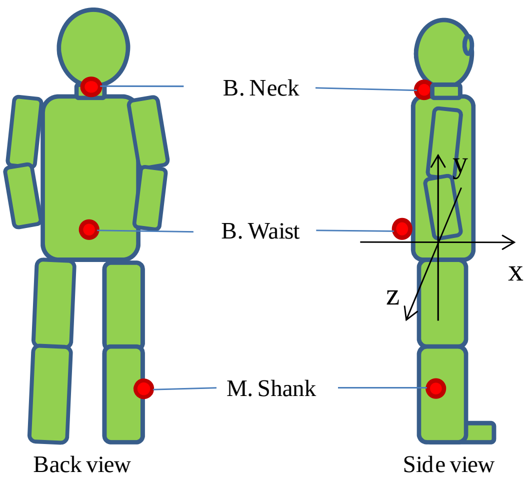

Fig. 2 Attachment of accelerometers on the body.

Accelerometers have been widely used to monitor body movements, including gait, sit-to-stand transfers, postural sway and falls. They have also been used to measure physical activity levels and to identify and classify movements performed by subjects [4-8]. In this study, the acceleration is measured by 3 wearable wireless 3-axis accelerometers (Motion Recorder MVP-RF8, Microstone Nagano, Japan) fixed on the midpoint of the right shank (M. Shank), the back of the waist (B. Waist), and the back of the neck (B. Neck), as shown in Fig. 2. Sampling rate of the sensor was 100 Hz. When the subject stands upright, the sensors' *x*-axis is front/back, *y*-axis up/down, and *z*-axis right/left. However, since the orientation of the sensors changes during walking, the coordination system will also change.

In the experiment, we examined the acceleration of hard fall-limping, a walking disability caused by leg length discrepancy. Shoe-height increasing is usually provided to the patients to compensate for leg length discrepancy in order to get correct gait pattern [9][10]. The same method was used to simulate hard fall-limping in the experiment. As shown in Fig.3, a shoe-height increasing simulator made of rubber and wood was fastened to the right shoe of the subject. The simulator is very important in testing our method since it does not endanger the safety of the disabled during the development phase of the method.

Two levels of hard fall-limpings were simulated in the experiment. Slight hard fall-limping was simulated with a 2 cm simulator, and severe hard fall-limping a 4 cm simulator. Totally, 3 statuses (Normal without simulator, Slight, and Severe) were examined. The weight of the 2 cm simulator and 4 cm simulator were 179.9 g and 201.3 g, respectively. The effect of the weight of the simulators can be neglected in the walking since the weights were small.

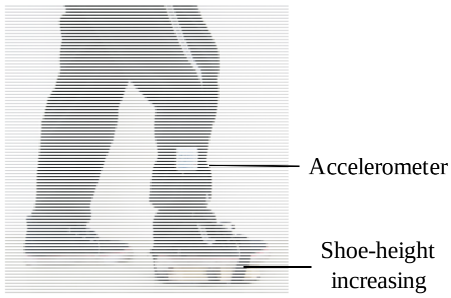

Fig. 3. Shoe-height increasing to simulate hard fall-limping.

Three healthy volunteers (S1, S2, and S3, 2 male and 1 female) aged 21-31 yr (mean 26 yr) participated in the experiment. Subjects were instructed to walk straight about 4m along a straight line. The experiment was carried in the status order of Normal, Slight, and Severe. For each status, each subject walked 10 times.

The measurement time-series data in *x* coordinate of the three sensors when subject S2 walked in the status of Slight are shown in Fig 4. The fluctuation of the acceleration was significant when the right foot or the left foot landing. There are 4 strides in Fig. 4. Acceleration data of the first stride are extracted and shown in Fig. 5. All the acceleration at the M. Shank, B. Waist and B. Neck significantly fluctuated when the right foot pushed off from the floor or stepped on the floor. The fluctuation in the acceleration at M. Shank was more significant than that at B. Neck, and the fluctuation in the acceleration at B. Neck was more significant than that at B. Waist. This showed that the trunk of the body, especially the waist, was relatively kept stable to maintain the body balance.

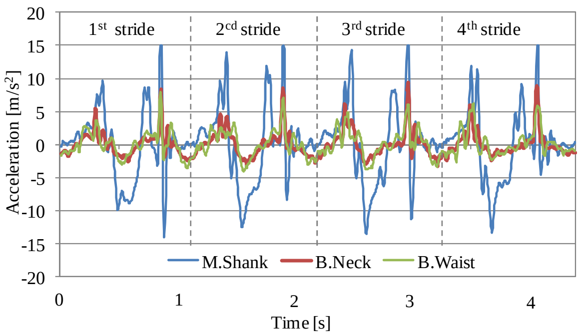

Fig. 4. X coordinate acceleration of S2 in the Slight status.

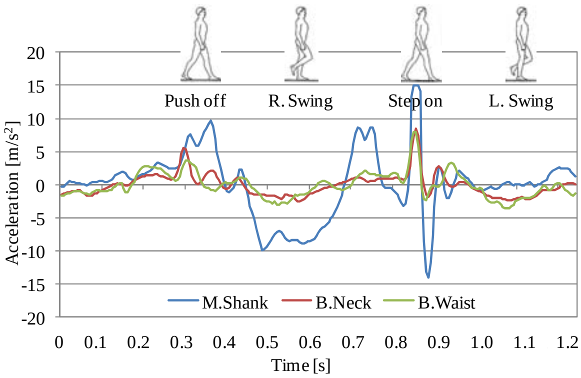

Fig. 5. Acceleration during the 1st stride.

3. Acceleration Analysis Using Singular Value Decomposition.

Singular value decomposition is used to acquire patterns from the time-series acceleration data. Suppose M is an m-by-n matrix. Then there exists a factorization of the form: $M = U\Sigma V^T$, where $U=(u_1, u_2, \ldots, u_m)$, $V=(v_1, v_2, \ldots, v_n)$, and the matrix Σ is m-by-n diagonal matrix with nonnegative real numbers on the diagonal [11][12]. The matrix U contains the left singular vectors of M and the matrix V contains the right singular vectors of M.

Suppose that there are w measurement points ($P_1, P_2, \ldots, P_w$). On point P_i, the measured data series of acceleration is denoted as A, which consists of 3-dimentional data (A_X, A_Y, A_Z). We detect the time series $A_X^i = (x_1^i, x_2^i, \ldots, x_n^i)^T$ contains the x coordinate values of the P_i point. Then matrix M_X^i is defined as a collective of the change of x coordinate values of the gesture, $M_X^i = (A_X^{i,1}, A_X^{i,2}, \ldots, A_X^{i,3})$.

The matrix M_X^i can be decomposed into a product of U_X^i, Σ_X^i and V_X^i. Let us denote the singular values and the left singular vectors as ($(\delta_X^{i,1}, u_X^{i,1})$, $(\delta_X^{i,2}, u_X^{i,2})$, $\cdots$, $(\delta_X^{i,l}, u_X^{i,l})$), for $u_X^{i,j} = (u_{X,1}^{i,j}, u_{X,2}^{i,j}, \cdots, u_{X,q}^{i,j})$ in descending order of the singular values. The parameter l represents the number of representative patterns under consideration, and the parameter q represents the number of elements of the singular vector. The left singular vectors $u_X^{i,1}$, $u_X^{i,2}$, … , $u_X^{i,l}$ of M_X^i, represent the change patterns of the x coordinate acceleration on point P_i. The bigger the singular value is, the more dominant the corresponding pattern is [11].

We use the same calculation on y and z coordinate accelerations to get ($(\delta_Y^{i,1}, u_Y^{i,1})$, $(\delta_Y^{i,2}, u_Y^{i,2})$, $\cdots$, $(\delta_Y^{i,l}, u_Y^{i,l})$) and ($(\delta_Z^{i,1}, u_Z^{i,1})$, $(\delta_Z^{i,2}, u_Z^{i,2})$, $\cdots$, $(\delta_Z^{i,l}, u_Z^{i,l})$). The singular values and singular vectors are used as criteria for evaluating the lower leg ROM.

We focused on the acceleration change around the time when the right foot pushed off and stepped on the floor. The acceleration data around push-off and step on were analyzed respectively. The matrix M was designed according to the local maximum turning points, as shown in Fig. 4 and Fig.5. In the experiment, it took the subjects 8-10 steps to walk 4m once, with each foot landing 4-5 times. The maximum turning points in the x coordinate data series of the right foot were considered as the marks of push-off and step-on. The first 3 push-offs and step-ons were considered in the analysis. The first 3 push-offs and step-ons are the number of row of M. The data from 0.50s before the maximum turning point to 0.50s after the maximum turning point were extracted as the number of column. Therefore, M was a matrix of 3 row vectors and 100 column vectors. For each turning point, 9 matrixes (3 sensors, each has 3 coordinates) were extracted. In this paper, only the first singular value and the first left singular vector were considered. Thus parameter l was 1.

Each subject walked 10 times for each status in the experiment. The average singular value and singular vector of the 10 times of walking were used in the analysis.

4. Results and Discussions

The first singular values extracted from the acceleration data around push-offs are listed in Table 1, and step-ons in Table 2.

Table 1 shows the great differences among the subjects in the singular values extracted from the acceleration data around push-offs. For example, the singular values of M. Shank in the front/back direction (Ax) of S2 and S3 increased with the increase of shoe-height. However, the singular values of S1 did not shown the same trend. The great individual differences are also show in Table 2. The importance of paying attention to individual characteristics in the analysis of walking ability is suggested because gait and stride are quite different during walking from person to person.

In spite of the individual differences in walking, similar singular changes of all the 3 subjects were shown in the right/left direction (Az) at M.Shank and B.Neck. The singular values of push-offs increased with the increase of shoe-height at M. Shank and B. Neck (Table 1.). The singular values of step-ons decreased with the increase of shoe-height at M. Shank, and increased with the increase of shoe-height at B. Neck (Table 2.).

There is no definite change in the singular values at B. Waist. It is indicated that the waist's movement was not affected significantly by the difference of leg length. The difference of leg length might be offset by the adjustment in the hip joint. The waist was kept stable might be because of the important role it played in keeping balance since the center of the body is located in the waist.

Table 1. First singular values of the acceleration data around push-offs

		M. Shank			B. Neck			B. Waist		
		Normal	Slight	Severe	Normal	Slight	Severe	Normal	Slight	Severe
Ax	S1	83.4 (3.1)	100.9 (9.1)	106.7 (13.7)	12.7 (1.5)	16.7 (1.2)	16.7 (2.0)	36.1 (1.5)	39.9 (2.2)	38.5 (2.3)
	S2	57.4 (3.1)	43.8 (3.9)	54.1 (6.7)	12.3 (1.2)	19.1 (2.7)	18.1 (2.8)	27 (2.4)	25.9 (1.8)	30.1 (3.4)
	S3	67.9 (5.2)	69.2 (5.1)	74.2 (5.9)	13.0 (1.8)	11.6 (2.2)	13.9 (2.1)	30.2 (0.7)	36.3 (2.4)	35.0 (2.6)
Ay	S1	82.0 (4.2)	85.7 (5.6)	91.0 (8.8)	27.2 (1.7)	30.3 (2.2)	33.7 (2.9)	29.7 (1.6)	31.9 (2.0)	33.8 (2.9)
	S2	76.1 (3.4)	67.3 (2.9)	77.0 (3.6)	25.1 (1.3)	20.2 (1.3)	22.5 (1.9)	28.6 (1.9)	22.6 (1.3)	25.3 (2.4)
	S3	60.2 (3.8)	58.7 (4.5)	72.1 (7.3)	27.3 (2.5)	23.3 (0.9)	25.6 (1.9)	33.6 (3.1)	29.8 (1.7)	35.0 (3.6)
Az	S1	31.1 (1.9)	47.5 (5.3)	51.8 (6.1)	12.8 (0.8)	12.9 (0.8)	14.5 (01.5)	37.6 (3.2)	32.7 (3.8)	32.6 (4.0)
	S2	30.9 (1.6)	34.8 (2.7)	38.6 (2.5)	18.3 (0.8)	20.3 (1.0)	20.3 (2.2)	20.9 (0.9)	20.3 (2.1)	20.2 (3.2)
	S3	27.2 (2.7)	34.0 (4.2)	42.1 (4.2)	12.4 (1.2)	15.2 (1.6)	17.6 (2.0)	25.7 (2.3)	28.7 (3.3)	35.2 (3.6)

**Mean (SD) of 10 times of walking

Table 2. First singular values of the acceleration data around step-ons

		M. Shank			B. Neck			B. Waist		
		Normal	Slight	Severe	Normal	Slight	Severe	Normal	Slight	Severe
Ax	S1	73.2 (5.0)	92.2 (6.6)	88.2 (4.8)	12.3 (1.2)	14.7 (1.1)	11.9 (1.5)	35.9 (2.4)	37.2 (1.8)	35.8 (2.4)
	S2	99.6 (7.0)	77.7 (8.0)	67.2 (3.0)	11.3 (0.7)	21.7 (2.7)	24.1 (2.7)	26.3 (1.6)	26.9 (1.1)	28.6 (1.2)
	S3	97.4 (8.7)	94.4 (5.1)	92.0 (4.4)	14.9 (2.2)	15.5 (2.7)	22.6 (2.6)	32.3 (1.9)	34.0 (2.1)	33.0 (2.0)
Ay	S1	76.1 (2.0)	78.2 (6.4)	82.9 (4.6)	31.6 (1.9)	33.1 (1.6)	24.9 (2.9)	37.1 (1.8)	34.2 (2.5)	25.6 (2.5)
	S2	54.9 (3.1)	45.4 (5.9)	44.3 (9.2)	25.4 (1.3)	30.5 (1.6)	32.2 (1.5)	28.2 (1.8)	31.8 (1.9)	33.9 (1.4)
	S3	49.4 (3.8)	57.9 (3.1)	74.0 (4.0)	23.5 (2.0)	19.1 (0.6)	19.3 (1.7)	30.2 (2.5)	27.2 (1.0)	30.9 (1.5)
Az	S1	48.1 (5.1)	43.4 (5.8)	41.2 (6.9)	14.9 (0.9)	16.0 (0.8)	16.8 (0.9)	36.4 (4.2)	30.7 (4.19	24.4 (5.9)
	S2	64.0 (3.7)	35.2 (5.1)	28.5 (3.6)	14.7 (0.7)	17.6 (1.1)	19.7 (1.9)	16.1 (1.9)	18.7 (2.3)	15.1 (1.6)
	S3	60.0 (8.1)	50.4 (5.9)	47.8 (4.4)	10.4 (1.5)	14.1 (1.5)	17.9 (2.9)	25.9 (3)	24.9 (1.3)	25.0 (1.7)

**Mean (SD) of 10 times of walking

The first singular values are suggested to be effective criteria to evaluate hard fall-limping. That is, when the foot pushes off the floor, in the right/left direction, the bigger the first singular values of at M.Shank and B.Neck, the more serious the hard fall-limping is. And when the foot steps on the floor, the smaller the first singular values at M.Shank and the bigger at B.Neck, the more serious the hard fall-limping is.

The first singular values extracted from the acceleration data in the right/left direction at M. Shank, B. Waist and B. Neck are plotted in 3D spaces in Fig. 6. Singular values of the 10 times of walking are plotted in different shape and color according to the 3 statuses. The average singular values of the 3 statuses are connected with black lines. Fig. 6 shows that the first singular values are clustered according to the statuses. Especially, on the dimensions of M. Shank and B. Neck, the clusters distinguish from each other more clearly. The line connecting the average values can be considered as severity line of hard fall-limping, although the line is different from person to person due to the individual difference in walking.

As stated above, the relationship between the first singular values extracted from the acceleration data and the levels of hard fall-limping were analyzed. The first singular vectors also related to the statuses. As examples, Fig. 7 shows the first singular vectors in right/left direction at B. Neck of S2. Great similarity was shown in the waveforms of each status. With the increase of shoe height, the waveforms of push-offs seem to become sharper with the maximum value being bigger and the baseline being higher, and the waveforms of push-offs seem to begin higher and end lower. This suggests that the severity of hard fall-limping might also be evaluated by the waveform of the first singular vectors. Hayashi et al. have proposed a method for acquiring knowledge of human behavior from time-series gesture data based on singular vectors [13]. We will study the usefulness of the proposed method in the evaluation of hard fall-limping in our future work.

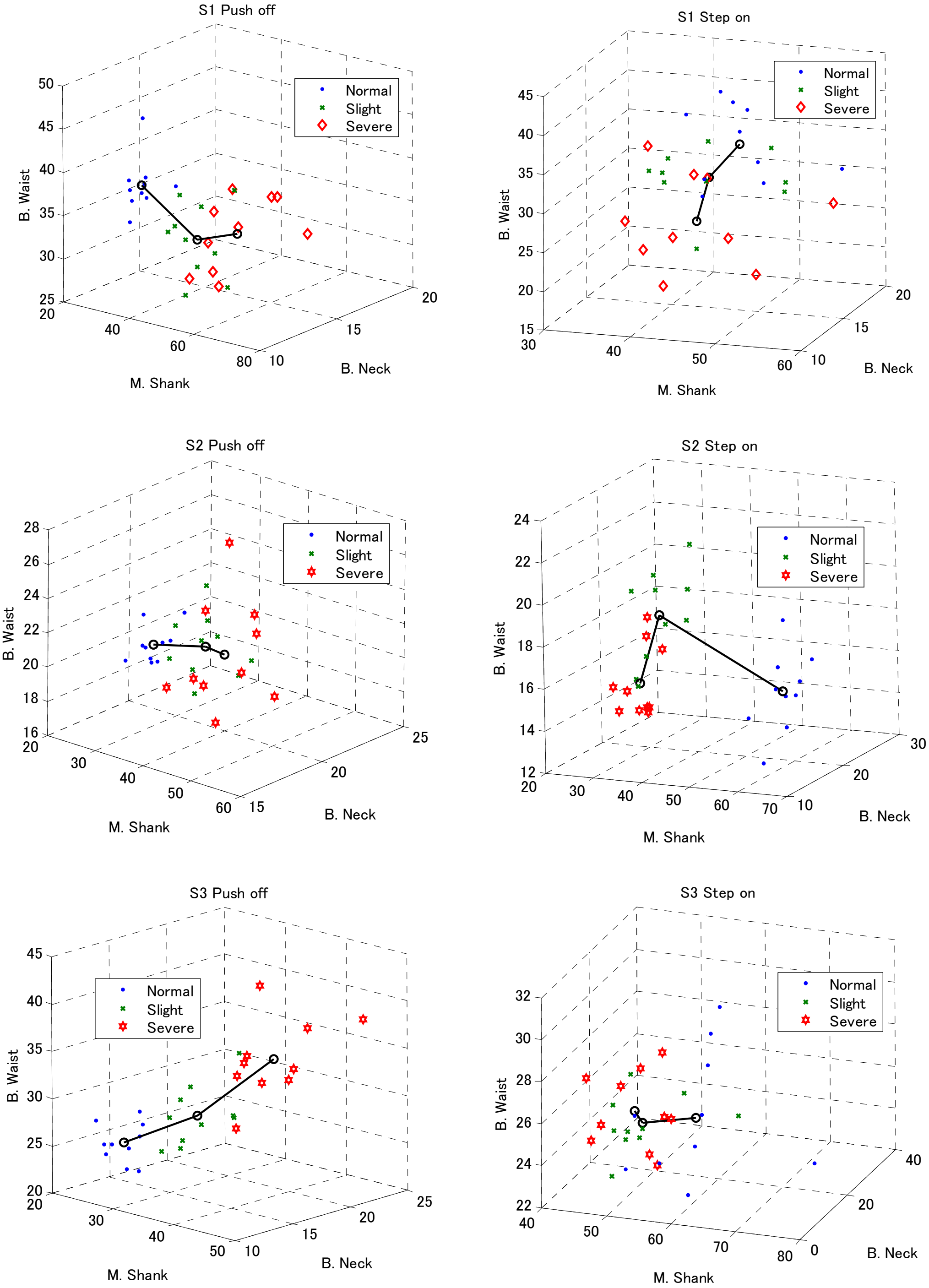

Fig. 6. First singular values from the acceleration data in the right/left direction at M. Shank, B. Waist and B. Neck.

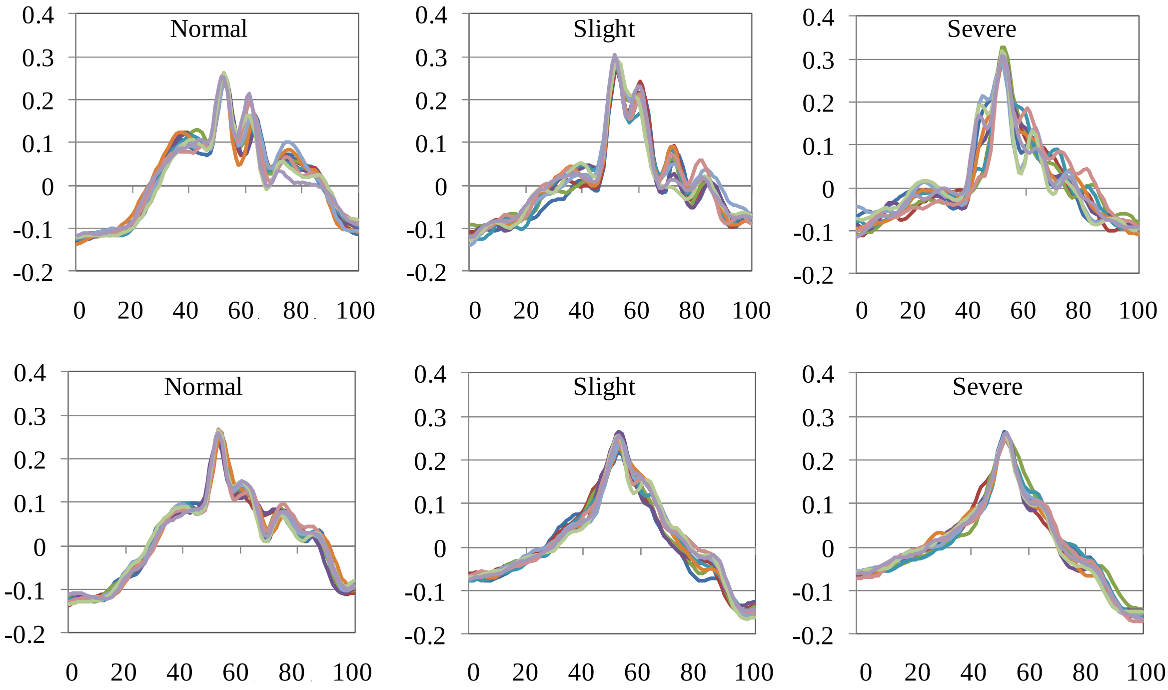

Fig. 7 First singular vectors in right/left direction at B. Neck of S2

5. CONCLUSIONS

A novel acceleration analysis algorithm using SVD is proposed for walking ability evaluation. The experiment results suggest that the first singular value inferred from the acceleration data in the right/left direction at M. Shank and B. Neck can be used as reliable criteria to evaluate hard fall-limping. Future studies will consider the segmentation of acceleration data and the evaluation of walking ability based on both singular vectors and singular values [13][14].

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