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Original Article

Classification of abnormal gait patterns of poststroke hemiplegic patients in principal component analysis

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ABSTRACT
Motoya R, Yamamoto S, Naoe M, Taniguchi R, Kawahara A, Iwata T. Classification of abnormal gait patterns of poststroke hemiplegic patients in principal component analysis. Jpn J Compr Rehabil Sci 2021; 12: 70−77.
Objective: The objective of this study was to classify the 10 types of characteristic abnormal gait by principal component analysis using quantitative indices of 10 types of abnormal gait.
Methods: For abnormal gait pattern classification, principal component analysis was performed using the deviation values of the 10 types of abnormal gait of 90 subjects. Scatter plots of the factor loadings of the 1st and 2nd principal components of the 10 types of abnormal gait were prepared, and those arranged at near sites were grouped based on the positional relationship, through which abnormal gait patterns were classified.
Results: It was suggested that abnormal gait patterns can be classified into insufficient knee flexion, hip hiking, and excessive lateral shift of the trunk over the unaffected side in the swing phase; knee extensor thrust pattern accompanying forefoot contact in the stance phase in addition to circumduction gait of the swing phase; and flexed knee gait pattern accompanying retropulsion of the hip in addition to median whip in the stance phase and excessive hip external rotation in the swing phase.
Conclusions: It was clarified by these principal component analyses that information contained in the results of the 10 quantitative indices of abnormal gait of the 90 poststroke hemiplegia patients was compressed into several abnormal gait patterns. If observational abnormal gait analysis is performed after understanding this gait pattern classification, it may help improve the accuracy of gait analysis by observation.
Key words: hemiplegia, abnormal gait patterns, gait analysis, 3-dimensional motion analysis, principal component analysis

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Introduction

In gait analysis of hemiplegic patients, observation of an abnormal gait pattern leads to observation of multiple abnormal gait patterns in many cases and these are considered associated with multiple characteristic abnormal gait patterns of hemiplegic patients. However, gait patterns of hemiplegic patients have been classified based on only knee joint movement of the affected side during the stance phase [1−3]; there has been no report in which various characteristic abnormal gait patterns of hemiplegic patients were comprehensively described. Quantitative assessment of abnormal gait patterns of hemiplegic patients encountered in observational gait analysis frequently performed at clinical sites and comprehensive interpretation of these may be desirable also for reducing inter-rater variation [4]. Thus, we focused on quantitative indices of abnormal gait acquired by 3-dimensional treadmill gait analysis [5]. In such analysis, at present, the feature values of 10 types of abnormal gait can be feature values for abnormal gait analysis [5]. Abnormal gait during the stance phase includes retropulsion of the hip, knee extensor thrust, flexed knee gait, forefoot contact, and medial whip; abnormal gait during the swing phase includes excessive lateral shift of the trunk over the unaffected side, insufficient knee flexion during the swing phase, hip hiking, circumduction gait, and excessive hip external rotation. Since clarification of the relationship among these using the feature values of the abnormal gait patterns acquired by this 3-dimensional treadmill gait analysis and its comprehensive interpretation for classification of abnormal gait patterns of hemiplegic patients lead to the observation of various abnormal

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gait patterns from the discovery of a characteristic abnormal gait at clinical sites, the information can be utilized also for improving the accuracy of observational abnormal gait analysis. The objective of this study was to classify the 10 types of characteristic abnormal gait by multivariate analysis using quantitative indices of 10 types of abnormal gait.

Methods

The subjects were 90 hemiplegic patients hospitalized in a convalescent ward between August 2016 and August 2019. Regarding the selection criteria, even though hemiplegic, patients with a past medical history of orthopedic disease were excluded. In the measurement method, after a therapist confirmed the treadmill gait of the subject and judged it as measurable, measurement was performed using a 3-dimensional treadmill gait analysis system (Fig. 1).

For the quantitative indices of abnormal gait of 3-dimensional treadmill gait analysis, 10 types [5] equipped in a 3-dimensional motion analysis device, Kinema Tracer®, as a standard program were used. For the 10 types of typical abnormal gait of hemiplegic patients, the calculation method corresponding to each definition has been devised after defining 10 types of typical gait based on literature as shown in Table 1. These analysis indices were prepared using kinematic factors including temporal-distance factor and trajectory of motion (Table 2) and highly correlated with 5-step ranks of severity observed by multiple physical therapists with many years of experience and skill in gait analysis, and its validity has been reported [6−9]. Since each quantitative index of abnormal gait is automatically calculated as a deviation value (= (patient's abnormal value − mean of healthy subjects) × 10/ SD + 50 of healthy subjects)) [10], comparison among abnormal gaits is possible as a product specification. Utilization of measurement data was explained to patients using an explanatory booklet at

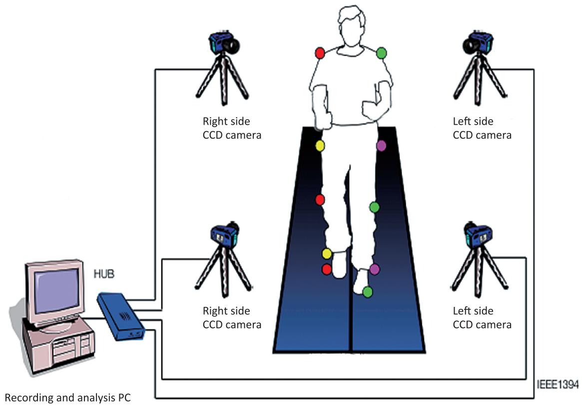

Figure 1. 3-dimensional motion analysis system [5]. KinemaTracer® is composed of a computer for recording and analysis, together with four CCD cameras. The computer and the CCD camera are only connected by an IEEE 1394 cable; synchronization between the cameras at the time of shooting is not required.

Table1. Definitions of index values representing the severity of abnormal gait [6−9].

Abnormal gait	Definition
Abnormal gait during the stance phase	
Retropulsion of the hip	The affected hip joint doesn't move continually forward over the affected ankle joint during loading response to mid-stance.
Knee extensor thrust	A dynamic, rapid knee extension during the loading response to terminal stance on the affected leg.
Flexed-knee gait	The knee remains in flexed position throughout the stance phase.
Forefoot contact	At initial contact, the forefoot on the affected side is the first to make contact, regardless of walking brace use.
Medial whip	The medial rotation of the ankle around the toe as a pivot during terminal stance to pre-swing.
Abnormal gait during the swing phase	
Excessive lateral shift of the trunk over the unaffected side	Trunk shifts excessively over the unaffected side during the swing phase of the affected side.
Insufficient knee flexion during the swing phase	A decreased maximum knee flexion angle during the swing phase.
Hip hiking	The pelvis on the affected side is raised during pre-swing to mid-swing, associated with shortening of the trunk on mid-stance.
Circumduction gait	The lower extremity of the affected side shows hip joint abduction and lateral rotation during initial swing to mid-swing and hip joint adduction and medial rotation during mid-stance to terminal swing, following a semicircular trajectory.
Excessive hip external rotation	A more excessive hip external rotation of the affected leg than normal throughout the entire swing phase.

Table 2. Calculation of index values representing the severity of abnormal gait [6−9].

Abnormal gait	Calculation for index values
Abnormal gait during the stance phase	
Retropulsion of the hip	The average distance between the X coordinate of the ankle joint and the X coordinate of the toe in the swing phase, corrected by lower limb length.[1]
Knee extensor thrust	The difference between the maximum Y coordinate velocity of the knee in the in the single stance phase and treadmill gait speed.
Flexed-knee gait	The maximum knee extension angle during single stance phase.
Forefoot contact	The difference in distance between the Z coordinate of the ankle joint marker and the Z coordinate of the toe marker at initial contact, minus the difference in distance between the Z coordinates the of the ankle joint marker and toe marker during standing.
Medial whip	The difference in distance between the medial-most X coordinate of the ankle marker during 25−75% of the stance phase and lateral-most X coordinate during 75−100% of the stance phase, corrected by foot length.[2]
Abnormal gait during the swing phase	
Excessive lateral shift of the trunk over the unaffected side	The average distance between (1) the lateral most X coordinate of the midpoint between the bilateral acromions in the part of the double stance phase in which the affected leg is located behind the unaffected leg and the swing phase of affected leg and (2) the average X coordinate of the midpoint between the bilateral ankle joints in the part of the double stance phase in which the affected leg is located behind the unaffected leg, corrected by lower limb length.[1]
Insufficient knee flexion during the swing phase	The percentage of the difference in the maximum knee flexion angle during swing phase between the case and the healthy subjects.
Hip hiking	The difference between the maximum value of the Z coordinate of the hip joint marker during the swing phase and the Z coordinate of the contralateral hip joint marker at the same time, corrected for the mean left-right difference of the Z coordinate during the double support phase.
Circumduction gait	The difference in distance between the lateral-most X coordinate of the ankle joint marker in 25−75% of the swing phase and the medial-most X coordinate in 25−75% of the stances phase, corrected by lower limb length.[1]
Excessive hip external rotation	The average distance between the X coordinate of the ankle joint and the X coordinate of the toe in swing phase, corrected by foot length.[2]

X, Y, and Z coordinates indicate lateromedial, anteroposterior, and vertical directions, respectively.
[1]Corrected by lower limb length: the index value was expressed as a percentage of the Z coordinate of the hip joint in a quiet standing position.
[2]Corrected by foot length: the index value was expressed as a percentage of the distance in the Y coordinate between the ankle joint and the toe in a quiet standing position.

the time of measurement and those who gave consent orally were selected for the subjects of this study. This study was performed after approval (17-Ig-129) by the Ethics Committee of the International University of Health and Welfare.

1. Statistical method

In general classification of multivariate analysis, principal component analysis is defined as a quantitative analysis technique aiming at integrating and classifying various variables without a response variable [11]. In principal component analysis, synthetic variables showing a high correlation with all considered variables and with a some of the considered variables were determined. A summary of variables can be performed using the former, i.e., the 1st principal component, and variable classification can be performed using the latter, i.e., the 2nd and latter principal components. In the classification method, principal component analysis is performed and the positions of variables of combinations of the principal components, such as the 1st and 2nd principal components and 1st and 3rd principal components, are plotted on an X−Y 2-dimensional plane. When the principal component is the same, the variables are arranged at near sites, whereas when the principal component is different, the variables are arranged at distant sites [11], and variables are grouped based on their positional relationship of these.

2. Statistical analysis method

For abnormal gait pattern classification, principal component analysis was performed using the deviation values of the 10 types of abnormal gait of the 90 subjects. For statistical analysis, JMP®12 (SAS Institute Inc., Cary, NC, USA) was used. For calculation of principal component analysis, correlation matrix was used. First, scatter plots of the factor loadings of the 1st and 2nd principal components of the 10 types of abnormal gait were prepared, and those arranged at near sites were grouped based on the positional relationship, through which abnormal gait patterns were classified. Similarly, scatter plots of factor loadings of the 1st and 3rd principal components were prepared. Then, the principal component score was calculated using the factor loadings acquired from the results of principal component analysis and Spearman's rank correlation coefficient of the relationship between the 1st and 3rd principal component scores and severity of motor paralysis was determined, setting the significance level at 5%.

Results

The attributes of the subjects were: males, 52; females, 38; age, 68.9±11.2 years old; time after onset (period from the onset to measurement), 64.5±31.5 days; and time of measurement after admission, 40.2±30.2 days (Table 3). The SIAS lower extremity paralysis total of the subjects was 10.5±3.8 and FIM gait at the time of measurement was 4.3±2.4. Twenty-nine subjects were orthosis users and 57 were handrail users.

The eigenvalue, contribution rate, and cumulative contribution rate of each principal component determined from the results of principal component analysis are shown in Table 4. Principal components with an eigenvalue of 1 or higher were the 1st to 3rd principal components and the cumulative contribution rate of the 1st to 3rd principal components was 62.9%.

Table 3. Patient characteristics.

Sex (Male/Female)	52/38
Age (years)	68.9±11.2
Time after onset (days)	64.5±31.5
Time of measurement after admission (days)	40.2±30.2
SIAS-LE total[1]	10.5±3.8
Total 0 to 5 points: Severe paralysis	11
Total 6 to 10 points: Moderate paralysis	26
Total 11 to 15 points: Mild paralysis	53
FIM-gait[2]	4.3±2.4
Use of a brace (yes/no)	29/61
Use of a handrail (yes/no)	57/33
Treadmill gait velocity (km/h)	1.4±0.7

[1]SIAS-LE total: A total scale of 6 grades (0−5 points) of the lower extremities included in the Stroke Impairment Assessment Set (SIAS) designed to assess motor paralysis. To assess lower extremity motor paralysis, the hip- flexion, knee-extension, and foot-pat tests were adopted: 0 points for no muscle contraction, 1 point for slight muscle movement, 2 points for performing tasks incompletely, 3 points for ability to perform tasks with difficulty, 4 points for ability to perform tasks with slight difficulty, and 5 points for no difficulty with tasks.
[2]FIM-gait: Functional Independence Measure–gait. To assess the gait ability, the FIM walk item in the FIM locomotion subscore was adopted. The FIM walk item is a seven-grade scale: 1 point for less than 25% of walking effort, 2 points for 25−50%, 3 points for 50−75%, 4 points for 75−100%, 5 points for walking under surveillance, 6 points for walking with aids, and 7 points for walking on their own.

Table 4. Eigenvalue, contribution rate and cumulative contribution rate.

Principal Component	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}
Eigenvalue	3.43	1.54	1.32	0.97	0.76	0.60	0.48	0.40	0.25	0.24
Contribution rate (%)	34.3	15.4	13.2	9.7	7.6	6.0	4.8	4.0	2.5	2.4
Cumulative contribution rate (%)	34.3	49.7	62.9	72.6	80.2	86.2	91.0	95.0	97.5	100

for JMP®12 (SAS Institure inc., Cary, NC, USA).

According to custom, a principal component with an eigenvalue of 1 or higher is considered meaningful [12], so the 1st to 3rd principal components were analyzed as described below.

1. Classification of abnormal gait patterns

Aiming at gait pattern classification, scatter plots of the factor loadings of the 1st and 2nd principal components and 1st and 3rd principal components of each abnormal gait index are shown in Figs. 2 and 3, respectively. Based on Fig. 2, in abnormal gait during the swing phase, insufficient knee flexion, hip hiking, and excessive lateral shift of the trunk over the unaffected side during the swing phase were positioned at near sites. In addition, the value of the 2nd principal component of circumduction gait was negative and that of the 2nd principal component of excessive hip external rotation was positive. Abnormal gait of excessive hip external rotation during the swing phase, and abnormality of medial whip, were positioned at near sites. In abnormal gait during the stance phase, the values of the 2nd principal components of retropulsion of the hip and flexed knee gait were positive, and those of the 2nd principal components of forefoot contact and knee extensor thrust were negative.

Based on Fig. 3, in abnormal gait during the stance phase, retropulsion of the hip, flexed knee gait, and forefoot contact were positioned at near sites. On the other hand, medial whip was positioned at a site opposite to these and knee extensor thrust was positioned at a site near the site of abnormal gait in the swing phase.

2. Association between the principal component score and severity of motor paralysis

Regarding the relationship between the principal component score and severity of motor paralysis in the 90 subjects, the relationships of the 1st to 3rd principal component scores with the severity of motor paralysis are shown in Fig. 4. A significant correlation was noted between the 1st principal component score and severity of motor paralysis (p<0.01). The 2nd and 3rd principal component scores were not significantly correlated with the severity of motor paralysis.

Discussion

1. Nature of principal component analysis

Regarding 1st principal component Z_1, the eigenvalue was large, the value was positive in all items of abnormal gait during the swing phase, and even when items of abnormal gait during the stance phase were combined, the value was positive in 8 of the 10 items. These are termed ‘size factor’ and considered to represent the ‘severity of abnormal gait’ in principal component analysis.

Regarding 2nd principal component Z_2, the values

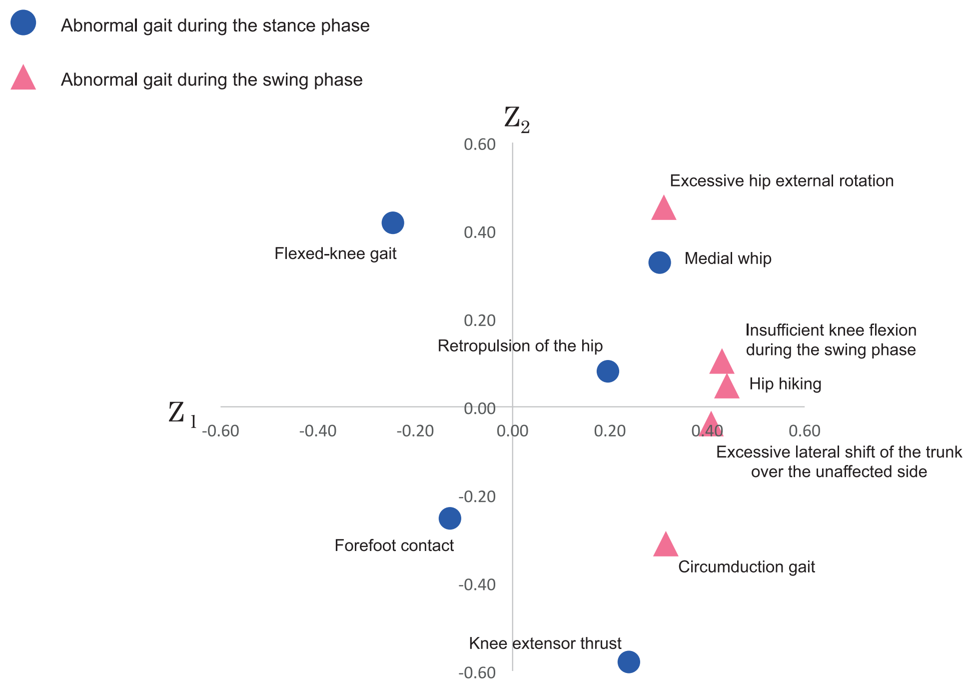

Figure 2. Plot of factor loadings of the 1st and 2nd principal components (Z_1, and Z_2) of the abnormal gait pattern.
The horizontal axis indicates the factor loading of the 1st principal component.
The vertical axis indicates the factor loading of the 2nd principal component.
The circles indicate abnormal gait during the stance phase.
The triangles indicate abnormal gait during the swing phase.

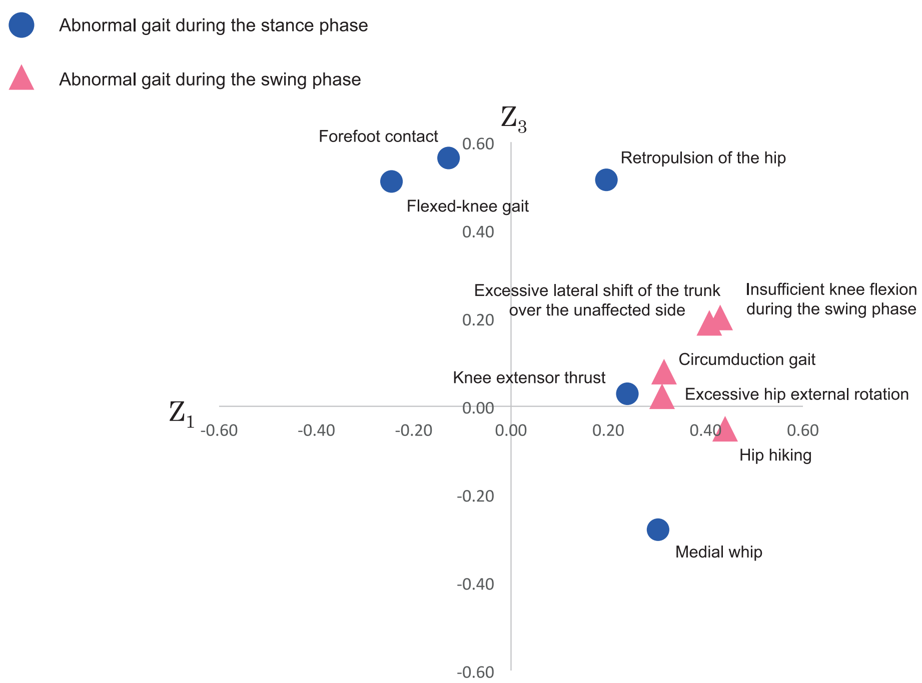

Figure 3. Plot of factor loadings of the 1st and 3rd principal components (Z_1, and Z_3) of the abnormal gait pattern.
The horizontal axis indicates the factor loading of the 1st principal component.
The vertical axis indicates the factor loading of the 3rd principal component.
The circles indicate abnormal gait during the stance phase.
The triangles indicate abnormal gait during the swing phase.

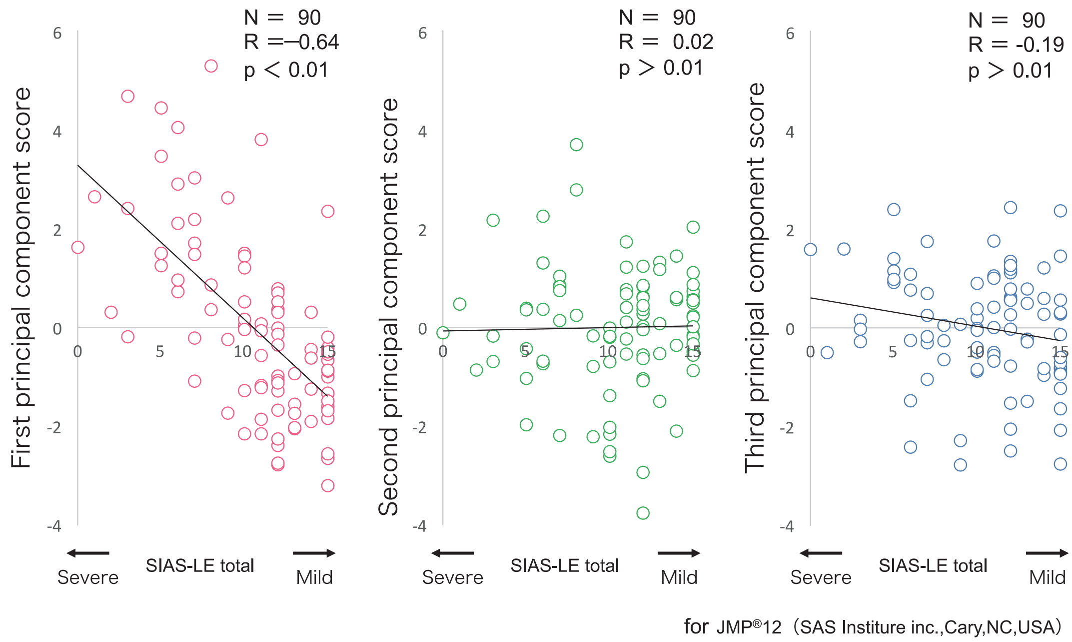

Figure 4. Association between principal component score and severity of motor paralysis (SIAS-LE total).
The vertical axis indicates the score of each principal component.
The horizontal axis indicates the SIAS-LE total.
White circles indicate the principal component score of each case.

of insufficient knee flexion, hip hiking, and excessive lateral shift of the trunk over the unaffected side during the swing phase were at near sites. In abnormal gait during the swing phase, the value of excessive hip external rotation was positive and that of circumduction gait was negative. In abnormal gait during the stance phase, the values of retropulsion of the hip, flexed knee gait, and medial whip were positive and those of forefoot contact and knee extensor thrust were negative, suggesting that these are factors representing hip joint movement in the swing phase and stance phase. Regarding 3rd principal component Z_3, the values of abnormal gait during the stance phase of retropulsion of the hip, flexed knee gait, and forefoot contact, were positive and that of medial whip was negative. On the other hand, the value was close to 0 in abnormal gait during the swing phase, suggesting that these are factors representing knee joint movement in the stance phase.

2. Classification of abnormal gait patterns

In gait pattern classification, the positional relationship between the 1st and 2nd principal components was analyzed using scatter plots of the factor loadings (Fig. 2) and it was suggested that abnormal gait patterns can be classified into the abnormal gait pattern of insufficient knee flexion, hip hiking, and excessive lateral shift of the trunk over the unaffected side in the swing phase; knee extensor thrust pattern accompanying forefoot contact in the stance phase in addition to circumduction gait of the swing phase; and flexed knee gait pattern (Fig. 5) accompanying retropulsion of the hip in addition to medial whip in the stance phase and excessive hip external rotation in the swing phase.

Since the scatter plots of the factor loadings of the 1st and 3rd principal components may represent abnormal gait during the stance phase, when it was considered based on the walking cycle of the stance phase, retropulsion of the hip, flexed knee gait, and forefoot contact were abnormal gait from early to mid-stance; knee extensor thrust was an abnormal gait pattern in the loading response over the terminal stance; and median whip was an abnormal gait pattern from mid-stance over pre-swing, when pattern classification was considered based on the time of appearance of the stance phase.

3. Integration and interpretation of data

These principal component analyses clarified that information contained in the results of the 10 quantitative indices of abnormal gait of the 90 poststroke hemiplegic patients was compressed to the severity of abnormal gait, hip joint movement in the stance phase, and abnormal gait pattern influenced by knee joint movement in the stance phase. By observing the positional relationship among these in the scatter plots of the factor loadings, these could be classified into three patterns of closely associated abnormal gait and these may be further classified into abnormal gait patterns based on the timing of appearance of the stance phase.

4. Clinical meaning of principal components

The correlation of the 1st principal component score with the severity of motor paralysis was high, the score increased as the severity of motor paralysis aggravated, and this was consistent with the fact that abnormal gait is aggravated in patients with severe motor paralysis, suggesting that the principal component score-based assessment is useful.

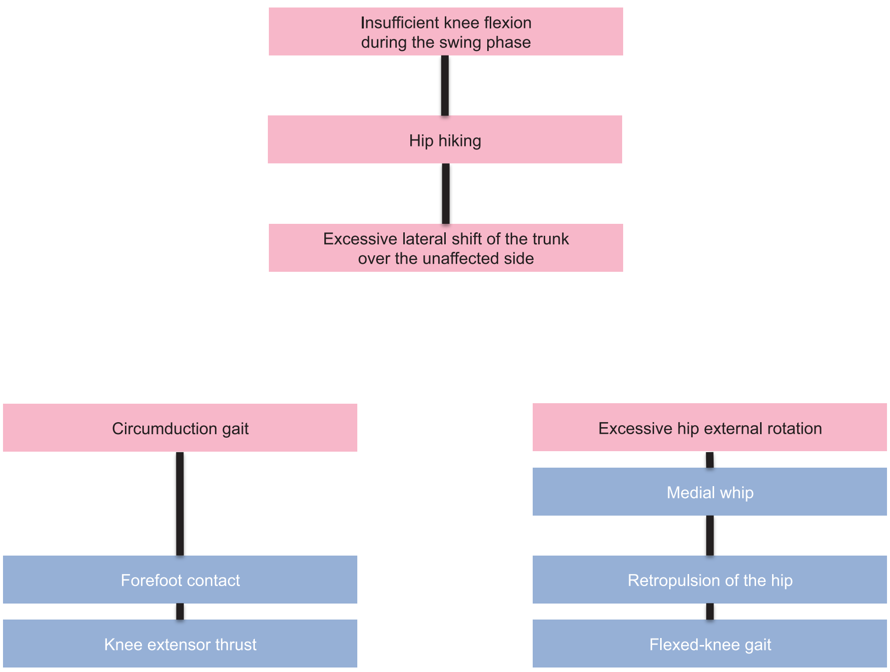

Figure 5. Classification of abnormal gait patterns in hemiplegic patients.

Conclusion

We tried to classify the characteristic abnormal gait patterns of poststroke hemiplegic patients based on the results of this study, but these results do not clarify the developmental mechanism based on which the patterns were classified. It is necessary to perform an analysis with more subjects, stratifying them with an evaluation of physical function and measurement condition in the future. It is also necessary to clarify the developmental mechanism by kinematic analysis and electromyographic analysis of typical cases of these patterns.

Information is lost in principal component analysis due to the characteristic that components are easy to explain in order from higher value, so it is necessary to take into consideration that about 37% of information is lost from the cumulative contribution rate of the 1st to 3rd principal components.

There were limitations in this study. Three-dimensional treadmill gait analysis was performed in only hemiplegic patients of our hospital and the results were acquired using indices of a 3-dimensional motion analysis device, Kinema Tracer®. Universality was insufficient and so should be verified in the future. Regarding quantitative indices of abnormal gait, only the 10 types of abnormal gait were used and not all abnormal gaits of hemiplegic patients encountered at clinical sites were covered. Regarding the effect of using assistive devices, we consider that a comparison within identical subjects is necessary, but it would be unethical to require patients with severe paralysis to walk without using an assistive device. Thus, it is evidently impossible to clarify all factors of abnormal gait of hemiplegic patients. However, if observational abnormal gait analysis is performed after understanding this gait pattern classification, the discovery of a characteristic abnormal gait pattern may lead to observation of the presence or absence of abnormal gait patterns of the classification, suggesting that the knowledge has sufficient meaning with regard to improving the accuracy of observational abnormal gait analysis.

Acknowledgments

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References

1. Mulroy S, Gronley J, Weiss W, Newsam C, Perry J. Use of cluster analysis for gait pattern classification of patients in the early and late recovery phases following stroke. Gait Posture 2003; 18: 114−25.
2. De Quervain IA, Simon SR, Leurgans S, Pease WS, McAllister D. Gait pattern in the early recovery period after stroke. J Bone Joint Surg 1996; 78A: 1506−14.
3. Tanaka S, Yamamoto S. Kinetics and electromyographic analysis of hemiparetic gait patterns in patients. J Soc Biomech 2016; 23: 107−17.
4. Tanikawa H, Otsuka K, Saitoh E, Itoh N, Yamada J, Muraoka Y, et al. Inter-rater reliability of visual inspection about abnormal gait. Sogo Rehabil 2010; 38: 1175−81.
5. Ohtsuka K, Saito E, Matsuda F, Kanada Y. Three-dimensional treadmill gait analysis. J Clin Rehabil 2014; 23: 871−9.
6. Itoh N, Kagaya H, Saitoh E, Ohtsuka K, Yamada J, Tanikawa H, et al. Quantitative assessment of circumduction, hip hiking, and forefoot contact gait using Lissajous figures. Jpn J Compr Rehabil Sci 2012; 3: 78−84.
7. Tanikawa H, Ohtsuka K, Mukaino M, Inagaki K, Matsuda F, Teranishi T, et al. Quantitative assessment of retropulsion of the hip, excessive hip external rotation, and excessive lateral shift of the trunk over the unaffected side in hemiplegia using three-dimensional treadmill gait analysis. Top Stroke Rehabil 2016; 23: 311−7.
8. Hishikawa N, Tanikawa H, Ohtsuka K, Mukaino M, Inagaki K, Matsuda F, et al. Quantitative assessment of knee extensor thrust, flexed-knee gait, insufficient knee flexion during the swing phase, and medial whip in hemiplegia using three-dimensional treadmill gait analysis. Top Stroke Rehabil 2018; 13: 1−6.
9. Saitoh E, Ohtsuka K. Gait analysis and motion analysis. Tokyo: Center for Academic Publications Japan, 2015: 71−88.
10. Ohtsuka K, Mukaino M, Tanikawa H, Saitoh E. Actual clinical gait analysis in physical therapy of central nervous system disease patients. Jpn J Phys Ther 2018; 35: 156−68.
11. Kaneko S. Outline of multivariate analysis centering principal component analysis, multiple regression analysis, and discriminant analysis. Vet Sci Stat Methods 1980; 5: 1−4.
12. Tsuchida T, Moriya H, Yoshinaga K, Kubota T. Quantitative evaluation of hemiplegic gait using principal component analysis. Jpn J Rehabil Med 1998; 35: 477−84.