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Original Article

Analysis of strategies used by hemiplegic stroke patients to achieve toe clearance

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ABSTRACT
Matsuda F, Mukaino M, Ohtsuka K, Tanikawa H, Tsuchiyama K, Teranishi T, Kanada Y, Kagaya H, Saitoh E. Analysis of strategies used by hemiplegic stroke patients to achieve toe clearance. Jpn J Compr Rehabil Sci 2016; 7: 111−118.
Objective: The purpose of this study was to analyze the extent to which lower limb shortening and compensatory movements contribute to toe clearance during swing, and to identify the different strategies employed by healthy individuals and hemiplegic stroke patients to achieve toe clearance.
Methods: The subjects comprised 18 hemiplegic stroke patients and 18 healthy individuals matched for age, gender, and walking speed. We calculated toe clearance and its components for comparison between the two groups. We also calculated the correlations between the components.
Results: The foot-to-floor distance during mid-swing was smaller in hemiplegic stroke patients than in healthy individuals. Regarding the components, shortening of hip–toe length (SHTL) was smaller in stroke patients, whereas upward movement of the hip due to pelvic obliquity, upward movement of the foot due to abduction, and upward movement of the contralateral hip were all greater. Among hemiplegic stroke patients, there were significant negative correlations between SHTL and the other components.
Conclusions: Hemiplegic stroke patients achieved smaller upward movement by lower limb shortening compared with healthy individuals. The contribution of hip hiking and other compensatory movements that correlated to SHTL appeared to be important in achieving toe clearance.
Key words: hemiplegia, toe clearance, compensatory movement, gait analysis

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Introduction

Toe clearance during the swing phase of the gait cycle is believed to affect tripping, which is a major cause of falls [1]. In healthy individuals, toe clearance is determined by flexion of the hip and knee joints and dorsiflexion of the ankle [2]. In patients with hemiplegia associated with cerebral stroke, flexion movements of the lower limb during swing are impaired, as evinced by the terms “Stiff-knee gait” (SKG) [3−6] and “drop foot” [7−9], and such patients are reported to exhibit characteristic movements including hip hiking [10−13] and circumduction [11,14]. These movements are interpreted as compensatory movements to achieve toe clearance by compensating for the diminished flexion movement of the lower limb [10−14]. When analyzing these movements, previous studies have expressed flexion movement of the lower limb as the angle of each joint, compensatory hip hiking as the obliquity of the pelvis [4, 10−13], and circumduction as the angle of the femur or the lateral distance that the foot moves [4, 10, 11, 13−15]. However, when considering the analysis of toe clearance, quantifying the actual effect of each movement on toe clearance would possibly provide findings that are more useful during rehabilitation assessments and interventions.

In this study, we assessed toe clearance as the totality of the shortening of the lower limb by joint movements during the swing phase and the various compensatory movements, and attempted to identify the different strategies employed to achieve toe clearance by hemiplegic stroke patients and healthy individuals matched for age, gender, and walking speed. This was achieved by analyzing the vertical components of the various types of movement related to toe clearance and investigating the degree to which each contributed to toe clearance. The amount of shortening of the hip–toe length (SHTL) [16] of the swinging lower limb was used as a representative value of the shortening of the lower limb due to joint movement [16]. Moreover, we calculated the actual perpendicular distance moved as a result of hip hiking and circumduction, and investigated differences in the patterns used to achieve toe clearance.

Subjects and Methods

1. Subjects

The study subjects were 18 hemiplegic chronic stroke patients who were capable of walking on a treadmill without using a handrail or orthosis, and 18 healthy individuals matched for age, gender, and walking speed (within ± 0.5 km/h), whose data was extracted from the Fujita Health University Department of Rehabilitation gait analysis database and used for analysis. The hemiplegic patients comprised 15 men and 3 women, 10 of whom were paralyzed on the right side and 8 on the left. Their mean age was 51 ± 13 years, mean height 166.9 ± 8.5 cm, mean weight 66.9 ± 13.7 kg, mean treadmill walking speed 2.3 ± 0.7 km/h, and mean Stroke Impairment Assessment Set lower limb motor score 9.2 ± 2.0. The mean time since stroke onset was 1,464 ± 1,217 (range 200−5,453) days. The healthy individuals were aged 51 ± 13 years; their mean height was 164.4 ± 6.4 cm, and their mean treadmill walking speed was 2.3 ± 0.7 km/h. This study was approved by the Institutional Review Board.

2. Methods

2.1 Devices and experimental procedure

Gait measurements were carried out using a Kinema Tracer® three-dimensional motion analysis system (Kissei Comtec Co. Ltd., Matsumoto, Japan). The Kinema Tracer® consists of recording and analysis software for use on a single personal computer and four charge-coupled-device cameras that are positioned around the treadmill. The subjects were instructed to walk on the treadmill without using a handrail or orthosis, and the three-dimensional coordinates of body markers were measured (X: left-right; Y: anterior/posterior; Z: superior/posterior). The markers, which were 30 mm in diameter, were applied at a total of 12 points: on both acromia, hips (at points one-third of the way from the greater trochanter of the femur along a line joining each anterior superior iliac spine with each greater trochanter), knees (on the midline of the anteroposterior diameter of each lateral epicondyle of the femur), ankles (lateral malleoli), toes (fifth metatarsal heads), and iliac crests (at the position of each iliac crest on a vertical line passing through the hips). The treadmill speed for hemiplegic patients was defined as their subjectively comfortable flat walking speed without the use of an assistive device, which was measured twice over 10 m and the mean value was used. Measurements were made over a 20-s period at a sampling frequency of 60 Hz.

2.2 Data analysis

The index values for swing on the paralyzed side were (1) foot-to-floor distance, (2) SHTL, (3) upward movement of the hip due to pelvic obliquity, (4) upward movement of the foot due to abduction, (5) upward movement of the contralateral hip, and the sum of the distances in (3), (4), and (5) (Figure 1). (1) The foot-to-floor distance was calculated from the Z-coordinate of the fifth metatarsal head as an index of toe clearance (Figure 1a). (2) SHTL was calculated as the distance between the hip and the fifth metatarsal head as an index of the sum of the flexion of the hip and knee and the dorsiflexion of the ankle (Figure 1b). (3) Upward movement of the hip due to pelvic obliquity was calculated from the Z-coordinates of both hips as an index of the upward movement of the hip on the swinging side as a result of pelvic obliquity (Figure 1c). (4) Upward movement of the foot due to abduction was calculated from the Z- and X-coordinates of the hip and the fifth metatarsal head as an index of the upward distance that the foot would have moved as a result of hip abduction had there been no change in lower limb length (Figure 1d). (5) Upward movement of the contralateral hip was calculated from the Z-coordinate of the contralateral hip as an index of the upward movement of the pelvis as a result of the extension of the opposite leg (Figure 1e). The calculation methods are given in Table 1. The total of

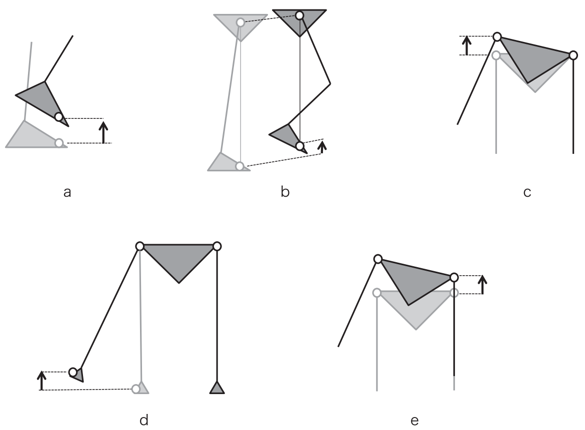

Figure 1. Toe clearance and its components.
Diagram of each index. In each illustration, the gray represents the position of the limb in mid-stance, while the black represents mid-swing. The circles indicate the markers.
(a) Foot-to-floor distance; (b) SHTL; (c) upward movement of the hip due to pelvic obliquity; (d) upward movement of the foot due to abduction; (e) upward movement of the contralateral hip. The indices are related by the equation a = b + c + d + e.
SHTL, shortening of hip-toe length.

Table 1. Methods of calculating the index values.

Index values	Markers	Calculation method (all values calculated as differences between mid-stance and mid-swing)
Foot-to-floor distance	Fifth metatarsal head	Z-coordinate value of the fifth metatarsal head
SHTL	Hip, Fifth metatarsal head	Direct distance between the hip and the fifth metatarsal head that was projected to the frontal plane
Upward movement of the hip due to pelvic obliquity	Hip, Contralateral hip	Difference between the Z-coordinate values of both hips
Upward movement of the foot due to abduction	Hip, Fifth metatarsal head	The difference between the Z-coordinate values of the hip and the fifth metatarsal head (hip–fifth metatarsal head) subtracted from the direct distance between the hip and the fifth metatarsal head that was projected to the frontal plane
Upward movement of the contralateral hip	Contralateral hip	The Z-coordinate value of the contralateral hip

the values obtained in (3), (4), and (5) was also calculated as an index of the upward movement other than limb shortening. In this study, the values for all indices were calculated as the differences between measurements made mid-stance and mid-swing on the paralyzed side in order to analyze the movements in the process of achieving toe clearance. The values for mid-stance on the paralyzed side were measured at the time that the fifth metatarsal head on the opposite side passed directly underneath the hip, and the values for mid-swing on the paralyzed side were measured at the time that the fifth metatarsal head on the paralyzed side passed directly underneath the hip. All these indices were calculated as values expressing change in the vertical direction. In healthy individuals, these values were calculated in the same way as with the left side. Pelvic obliquity at mid-stance on the paralyzed side in hemiplegic patients or the left side in healthy subjects (the difference between the Z-coordinates of both hips), the angle of flexion of the hips and knees, and the angle of dorsiflexion of the ankles were also calculated.

To identify the characteristics of the movements employed by hemiplegic stroke patients to achieve toe clearance, we used Student's *t*-test to compare the various indices between hemiplegic stroke patients and healthy individuals. To investigate the correlations between the components of toe clearance, Pearson's correlation coefficient was calculated between the values obtained for (2) and those for (3), (4), (5), and (3) + (4) + (5). Student's *t*-test was used to compare the pelvic obliquity at mid-stance on the paralyzed side and the joint angles of the lower limbs between hemiplegic patients and healthy individuals. JMP 11 software (SAS Institute Inc., Cary, NC, USA) was used for statistical analysis, with a 5% significance level.

Results

A comparison of the components of toe clearance showed significant differences between hemiplegic patients and healthy individuals for all the indices measured: mean foot-to-floor distance, 3.4 ± 1.4 vs. 7.9 ± 3.2 cm; mean SHTL, −0.4 ± 2.4 vs. 7.5 ± 3.0 cm; mean upward movement of the hip due to pelvic obliquity, 2.7 ± 1.8 vs. 1.3 ± 1.2 cm; mean upward movement of the foot due to abduction, 0.3 ± 0.3 vs. −0.3 ± 0.2 cm; and mean upward movement of the contralateral hip, 1.0 ± 1.9 vs. −0.7 ± 0.6 cm. Significant differences were confirmed in all index values (Figure 2). The foot-to-floor distance and SHTL were both smaller in hemiplegic patients than in healthy individuals ($p < 0.0001$ for both), whereas upward movement of the hip due to pelvic obliquity, upward movement of the foot due to abduction, and upward movement of the contralateral hip were all greater ($p = 0.0112$, < 0.0001, and $= 0.0013$, respectively). An examination of the various components of toe clearance revealed elongation of the lower limb in patients with particularly severe paralysis, with a corresponding tendency for compensatory factors to play a greater role in toe clearance. The proportion of the components of compensatory movements varied greatly between patients (Figure 3). In hemiplegic patients, there were significant correlations between SHTL and upward movement of the foot due to abduction ($r = -0.56$, $p = 0.0164$), upward movement of the contralateral hip ($r = -0.48$, $p = 0.0435$), and the sum of the upward movement of the hip due to pelvic obliquity, upward movement of the foot due to abduction, and upward movement of the contralateral hip ($r = -0.81$, $p < 0.0001$) (Figure 4). A comparison of mid-stance on the paralyzed side revealed significant differences in hip pelvic obliquity and hip flexion angle in hemiplegic patients ($p = 0.0227$ and 0.0103, respectively). In both cases, these were greater in hemiplegic patients than in healthy individuals (Table 2).

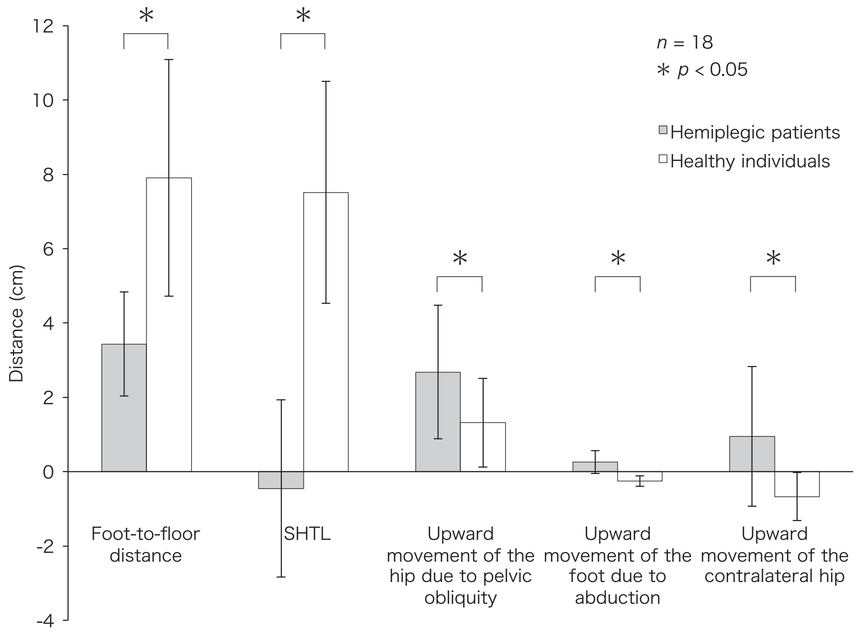

Figure 2. Comparison of toe clearance components in hemiplegic patients and healthy individuals.
Mean values of the foot-to-floor distance and its components in hemiplegic patients and healthy individuals. The gray graphs represent hemiplegic patients, and the white graphs represent healthy individuals. *$p < 0.05$.

Discussion

We quantified the various movements in the vertical direction that facilitate the achievement of toe clearance during swing in hemiplegic stroke patients and healthy individuals, and compared their relative contributions to toe clearance. Toe clearance on the paralyzed side was smaller in hemiplegic patients than in healthy individuals. In terms of the components of toe clearance, SHTL was smaller in hemiplegic patients than in healthy individuals, whereas upward movement of the hip due to pelvic obliquity, upward movement of the foot due to abduction, and upward movement of the contralateral hip were greater. In hemiplegic patients, there were significant negative correlations between SHTL and the other components.

SHTL, which reflected the functional impairment of the swinging lower limb, exhibited a negative value in more than half the patients in this study. A negative value for SHTL signifies the extension of the lower limb during swing, and in most hemiplegic patients in this study, compensatory movements were the main components of toe clearance.

All of the components other than SHTL, on the other hand, showed greater values in hemiplegic patients than in healthy individuals, reflecting increased compensatory movements to make up for the functional impairment of the lower limb. However, there were differences in the magnitude of the components considered to represent compensatory movements, and the effect that they exerted on toe clearance varied. In hemiplegic patients, upward movement of the hip due to pelvic obliquity exhibited the highest value, suggesting the importance of hip hiking as a compensatory movement [13]. Although upward movement of the foot due to abduction, which is considered to reflect circumduction, was greater in hemiplegic patients than in healthy individuals, the mean value in hemiplegic patients was only 0.3 ± 0.3 cm, suggesting that the contribution to toe clearance was rather small.

Circumduction is generally recognized as a compensatory movement during the swing phase, and one possible reason for our finding may be the timing of the assessment. In this study, we investigated the difference between values measured mid-stance and mid-swing, and it is possible that the effect exerted by circumduction is greater at toe-off than at mid-swing.

Another possible factor is that circumduction may not in itself constitute a compensatory movement, but rather a contingent phenomenon caused by abnormal muscle synergy. Previous studies have identified coupling between knee flexion and adductor muscle activity in stroke patients in the toe-off posture [17], and assistance with knee flexion during toe-off has also been reported to increase circumduction [4], suggesting that hip abduction may be a phenomenon associated with abnormal muscle synergy. Further studies are required to determine the extent to which circumduction actually functions as a compensatory movement.

As described above, we found that upward hip movement due to pelvic obliquity had a major effect on toe clearance in hemiplegic patients. Previous

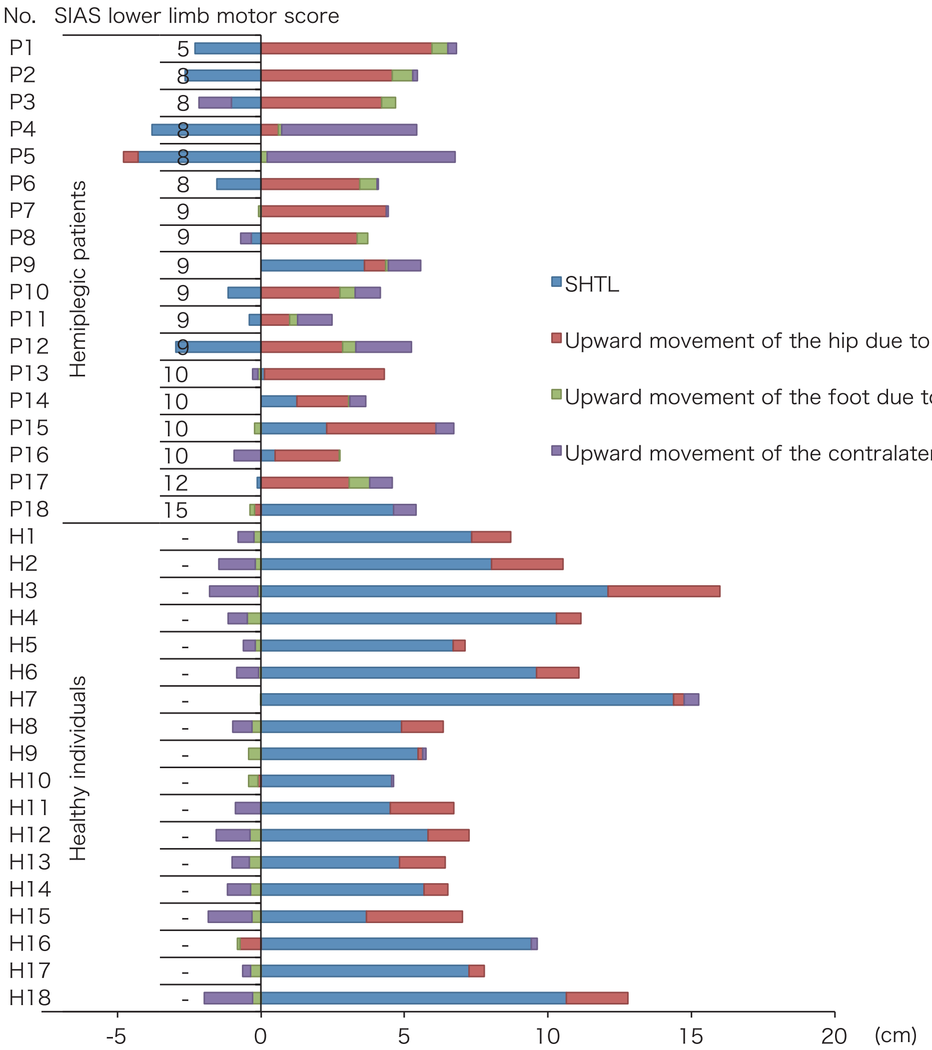

Figure 3. Toe clearance components in all patients.
Toe clearance components in all hemiplegic patients and healthy individuals (blue, SHTL; red, upward movement of the hip due to pelvic obliquity; green, upward movement of the foot due to abduction; purple, upward movement of the contralateral hip). A negative value indicates that the component concerned acts to reduce the toe clearance (such as lower limb extension or depression of the pelvis).

studies that mentioned hip hiking as compensation during swing were generally referring to elevation of the position of the hip due to obliquity of the pelvis [10, 12]. However, a few patients elevated the hip by extending the lower limb on the non-paralyzed side during swing, instead of by pelvic obliquity. To extract this component from the hip elevation, we calculated the upward movement of the contralateral hip in this study. In hemiplegic patients, this distance was much smaller than the elevation by pelvic obliquity, suggesting that it may not have made a major contribution to toe clearance as a compensatory movement. Upward movement of the contralateral hip was particularly large, however, in the two patients with the smallest SHTL (P4 and P5 indicated in Figure 3), suggesting that a pattern of achieving toe clearance with upward movement of the pelvis itself may be observed in a certain portion of hemiplegic patients with diminished lower limb function.

The indices investigated in this study were calculated as the differences between measurements made mid-stance and mid-swing, as identifying the magnitude of the change from the stance phase to the swing phase would allow us to ascertain the types of movements of the lower limb and pelvis employed to achieve toe clearance. For example, when the stance phase on the paralyzed side is managed with the knee flexed, the length of the lower limb during the stance phase is shortened by this knee flexion, and a compensatory movement between the stance phase and the swing phase is required to make up for this and achieve toe clearance. Looking at the difference between the stance phase and the swing phase clarifies that in cases such as this, the value becomes negative, reflecting the relative lengthening of the opposite lower limb and explaining the greater compensatory movement. In

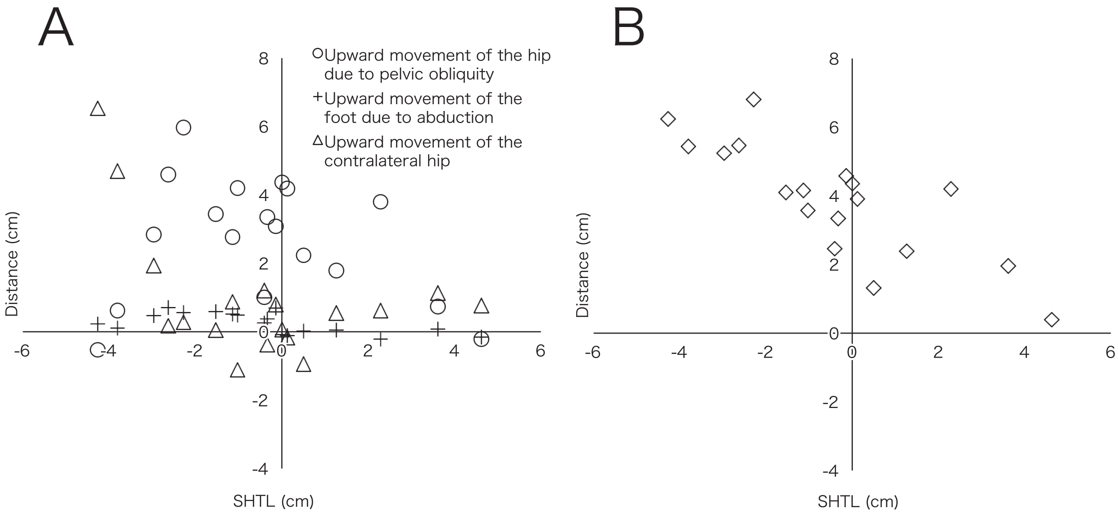

Figure 4. Correlations between SHTL and compensatory components.
In hemiplegic patients, SHTL was correlated with the various compensatory components as well as the sum of those compensatory components. (A) Correlations between SHTL and each compensatory component (circles, upward movement of the hip due to pelvic obliquity; crosses, upward movement of the foot due to abduction; triangles, upward movement of the contralateral hip. (B) Correlation between SHTL and the sum of the compensatory components.

Table 2. Pelvic obliquity and lower limb joint angles in mid-stance phase.

Index	Hemiplegic patients	Healthy individuals	*: $p < 0.05$
Pelvic obliquity (cm)	0.8 ± 2.0	−0.4 ± 0.8	*
Hip flexion (°)	5.5 ± 6.2	1.0 ± 3.4	*
Knee flexion (°)	5.3 ± 11.4	4.1 ± 4.7	
Ankle dorsiflexion (°)	0.4 ± 8.2	−2.9 ± 3.2	

Pelvic obliquity refers to the difference between the Z-coordinates of both hips (paralyzed side–opposite side). The angles of each joint are projected to the sagittal plane.
(mean ± standard deviation)

fact, SHTL and the sum of the compensatory movements calculated from the differences in this way reflected the tradeoff between the two, exhibiting a strong negative correlation.

The use of differences as indices, however, means that they may be affected by issues such as Trendelenburg's gait, which appears during the stance phase on the paralyzed side. In fact, mid-stance pelvic obliquity on the paralyzed side was greater in hemiplegic patients than in healthy individuals, and its interpretation requires caution. Furthermore, as these indices are not necessarily zero in healthy individuals, further studies are required to validate their method of interpretation, including the determination of normal values.

In this study, we found that in hemiplegic stroke patients, there was a strong negative correlation between SHTL and the sum of the indices of other compensatory movements, comprising upward movement of the hip due to pelvic obliquity, upward movement of the foot due to abduction, and upward movement of the contralateral hip.

However, the level of correlation with individual components was only moderate, reflecting a variation in the patterns of compensatory movements to make up for the reduction in SHTL. Thus, in order to understand the magnitude of and changes in compensatory movements, it is insufficient to assess individual compensatory patterns alone; evaluation must address the total extent of compensatory movements. In this study, calculating the components of toe clearance as values along a single vertical axis allowed us to evaluate the types of movements by which toe clearance was achieved and to assess their relative proportions.

Quantifying the level of impairment and the contribution of compensatory movements in this way may assist in making suggestions for exercises based on screening. For example, if an exercise increased the amount of shortening of the lower limb, this would theoretically enable a reduction in its compensatory movements. However, in clinical practice, it is difficult to explore such an optimum balance on the evidence of visual observation alone. The quantification of such changes, however, may enable the use of exercises with clear goals set based on the results of monitoring. Our approach can be expected to both provide an understanding of toe clearance strategies used by individual patients during walking and contribute to the establishment of exercise plans tailored to patients' disabilities.

Limitations of the Study

This study had a number of limitations. The first was that the tests were performed on a treadmill, which may have caused some differences in gait pattern compared with ground walking. This study was also limited to patients who were capable of walking without the use of an orthosis or handrail, leading to bias in the severity of disability in subjects. We were, nevertheless, able to demonstrate differences in the strategies employed by healthy individuals and hemiplegic patients during walking. We intend to carry out more detailed investigations of the differences between patterns in the future.

The trajectory of the toes in healthy individuals follows a downward-pointing curve during mid-swing, and as the minimum value of toe clearance occurs in mid-swing, studies investigating toe clearance have generally used the minimum toe clearance (MTC) as its representative value [18−20]. In some of our most severely paralyzed patients, however, the swing phase trajectory already followed an upward-pointing curve, making it difficult to calculate the MTC. We therefore used the distance between the toes and the floor when the toes passed directly underneath the hips as the representative value for toe clearance. This was because the distance between the hip and the floor on a line passing through the hips and the toes was shortest at this time point, and maximum shortening of the lower limb was required. Our study suggested that toe clearance was smaller in hemiplegic patients than in healthy individuals, but this result was not necessarily consistent with that of previous studies [13, 16]. This divergence in results may have been affected by the fact that our study subjects were more severely paralyzed than those reported in the previous studies, or that we evaluated treadmill walking, which is more difficult than ground walking, or by differences in calculation methods. Further studies are required to confirm the validity of this index as an indicator of toe clearance. However, our results are significant at least from the viewpoint of ascertaining the strategies employed to achieve mid-swing toe clearance and of analyzing their components.

Conclusions

We identified differences in the strategies employed by healthy individuals and hemiplegic stroke patients to achieve swing-phase toe clearance while walking. We also ascertained the extent to which the different types of compensatory movements contributed to toe clearance. Graphical representation of the actual effects of the various components of toe clearance, as performed in this study, may help to clarify the mechanisms of toe clearance in individual patients and in considering intervention targets for rehabilitation and evaluating the effectiveness of such interventions.

References

1. Barrett RS, Mills PM, Begg RK. A systematic review of the effect of ageing and falls history on minimum foot clearance characteristics during level walking. Gait Posture 2010; 32: 429−35.
2. Moosabhoy MA, Gard SA. Methodology for determining the sensitivity of swing leg toe clearance and leg length to swing leg joint angles during gait. Gait Posture 2006; 24: 493−501.
3. Kerrigan DC, Frates EP, Rogan S, Riley PO. Spastic paretic stiff-legged gait: biomechanics of the unaffected limb. Am J Phys Med Rehabil 1999; 78: 354−60.
4. Sulzer JS, Gordon KE, Dhaher YY, Peshkin MA, Patton JL. Preswing knee flexion assistance is coupled with hip abduction in people with stiff-knee gait after stroke. Stroke 2010; 41: 1709−14.
5. Tok F, Balaban B, Yaşar E, Alaca R, Tan AK. The effects of onabotulinum toxin A injection into rectus femoris muscle in hemiplegic stroke patients with stiff-knee gait: a placebo-controlled, nonrandomized trial. Am J Phys Med Rehabil 2012; 91: 321−6.
6. Campanini I, Merlo A, Damiano B. A method to differentiate the causes of stiff-knee gait in stroke patients. Gait Posture 2013; 38: 165−9.
7. Bethoux F, Rogers HL, Nolan KJ, Abrams GM, Annaswamy TM, Brandstater M, et al. The effects of peroneal nerve functional electrical stimulation versus ankle-foot orthosis in patients with chronic stroke: a randomized controlled trial. Neurorehabil Neural Repair 2014; 28: 688−97.
8. Martin KD, Polanski W, Schackert G, Sobottka SB. New therapeutic option for drop foot with the ActiGait peroneal nerve stimulator — a technical note. World Neurosurg 2015; 84: 2037−42.
9. Kottink AI, Oostendorp LJ, Buurke JH, Nene AV, Hermens HJ, IJzerman MJ. The orthotic effect of functional electrical stimulation on the improvement of walking in stroke patients with a dropped foot: a systematic review. Artif Organs 2004; 28: 577−86.
10. Stanhope VA, Knarr BA, Reisman DS, Higginson JS. Frontal plane compensatory strategies associated with self-selected walking speed in individuals post-stroke. Clin Biomech 2014; 29: 518−22.
11. Kerrigan DC, Frates EP, Rogan S, Riley PO. Hip hiking and circumduction: quantitative definitions. Am J Phys Med Rehabil 2000; 79: 247−52.
12. Chen CL, Chen HC, Tang SFT, Wu CY, Cheng PT, Hong WH. Gait performance with compensatory adaptations in stroke patients with different degrees of motor recovery. Am J Phys Med Rehabil 2003; 82: 925−35.
13. Cruz TH, Dhaher YY. Impact of ankle-foot-orthosis on frontal plane behaviors post-stroke. Gait Posture 2009; 30: 312−6.
14. Chen G, Patten C, Kothari DH, Zajac FE. Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds. Gait Posture 2005; 22: 51−6.
15. 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.
16. Little VL, McGuirk TE, Patten C. Impaired limb shortening following stroke: what's in a name? PloS one 2014; 9: e110140.
17. Cruz TH, Dhaher YY. Evidence of abnormal lower-limb torque coupling after stroke: an isometric study. Stroke 2008; 39: 139−47.
18. Winter DA. Human balance and posture control during standing and walking. Gait Posture 1995; 3: 193−214.
19. Mills PM, Barrett RS, Morrison S. Toe clearance variability during walking in young and elderly men. Gait Posture 2008; 28: 101−7.
20. Begg R, Best R, Dell'Oro L, Taylor S. Minimum foot clearance during walking: strategies for the minimisation of trip-related falls. Gait Posture 2007; 25: 191−8.