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CHAPTER 3

FUNCTIONAL RECOVERY OF GAIT AND JOINT KINEMATICS AFTER RIGHT HEMISPHERIC STROKE

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ABSTRACT

The objective of the present study was to gain insight into the relation between changes in gait patterns over time and functional recovery of walking ability in stroke patients. Thirteen stroke patients, admitted or awaiting admission for inpatient rehabilitation three weeks post stroke, and 16 healthy control subjects were included in the study. At 3, 6, 12, 24, and 48 weeks post stroke functional recovery of walking ability was assessed with the Rivermead Mobility Index (RMI) and the Functional Ambulation Categories (FAC). When possible, kinematics of the knee, hip and pelvis were assessed through gait analysis in an 8x4m gait lab. Minimal scores of 8 on the RMI and 4 on the FAC were necessary before patients were classified as functionally recovered. The results showed that patients, whose joint kinematics during ambulation had recovered to within the range of the control group, all showed functional recovery of walking ability. However, some patients whose kinematics had developed towards an abnormal pattern also showed functional recovery. We conclude that the recovery of joint kinematics towards a normal pattern is not a requirement for functional recovery of walking ability. Early recognition of compensatory walking patterns that facilitate functional recovery may have implications for rehabilitation programs.

INTRODUCTION

Regaining walking ability is of great importance to stroke patients and is a major goal in all rehabilitation programs.^{1,2} Although the reported figures vary, approximately 50-80% of patients who survive a stroke will eventually regain some degree of walking ability.³ Several studies have shown that most of the motor recovery occurs within the first 3 months post-stroke, and that the initially steep recovery curve levels at about 6 months to a year post-stroke.³⁻⁷

Recovery of walking ability is often quantified with clinical measures, such as the Rivermead Mobility Index⁸ (RMI) or the Functional Ambulation Categories⁹ (FAC), but gait velocity is also often used as a measure of recovery.¹⁰ Another way to record recovery of gait after stroke is through gait analysis, in which the specific characteristics of hemiplegic gait patterns can be analyzed. Several studies have been performed in which classifications of different types of hemiplegic gait patterns in stroke patients were suggested.¹¹⁻¹⁴ However, much is still unknown about the relation between the changes in gait patterns over time and functional recovery of walking ability in stroke patients. The aim of this study, therefore, was to gain more insight into this relation. The study addressed the changes that take place in joint kinematics in the first year post-stroke and how they relate to the recovery of functional walking ability.

Though gait patterns between stroke patients may vary greatly, some specific movement patterns can be observed in sub-groups of patients, and a number of studies have attempted to classify these hemiplegic gait patterns. In their review Olney and Richards¹² concluded that, concerning patterns in joint kinematics, hemiplegic gait can be classified by a combination of: (1) a reduced hip joint angle amplitude in the sagittal plane, caused by a decreased hip flexion at heel-strike and a decreased hip extension at toe-off; (2) a reduced knee joint angle amplitude caused by increased knee flexion at heel-strike and decreased knee flexion at toe-off and during swing; and (3) increased plantar flexion of the ankle at heel-strike and during swing and decreased plantar flexion at toe-off. Abnormalities in these joint kinematics often lead to secondary compensations in other body segments.

For example, reduced knee flexion during swing can be accompanied by circumduction, vaulting, or upward pelvic tilt.^{15,16} These secondary compensations may be energy inefficient in a normal healthy gait pattern. In a stroke patient, however, structural changes have taken place in the central nervous system so that the changed motor patterns may reflect adaptations that are optimal for the altered state of the system. The relation between the recovery of joint kinematics and functional recovery of walking ability might therefore be not as straightforward as one might think, and the observed kinematic changes towards a compensatory pattern that differs from the normal pattern might even facilitate functional recovery of walking ability.

In the present study recovery of knee and hip joint kinematics in stroke patients were recorded and compared with functional recovery of walking ability as measured with the FAC and the RMI. Furthermore, pelvic rotation in the sagittal plane was recorded because it was expected that pelvic rotation might be used to compensate for a reduced hip joint angle amplitude in the sagittal plane.

METHODS

Subjects

The present study was part of a larger study in which the effects on gait of hemi-neglect in right hemisphere stroke patients was researched. The patients in the present study formed a control group in the larger study and was comprised, therefore, only of right hemisphere stroke patients. Patients were included by screening all stroke patients at the neurological wards of two local hospitals and if they met the inclusion criteria they were asked to participate in the study. Patients had to (1) be within 20 to 80 years of age; (2) have suffered a first time, single right hemisphere cerebrovascular accident; (3) have no severe cognitive disorders that would have interfered with the study's purpose; (4) have no other pre-morbid disorders that would have affected the study's results; and (5) have been admitted for inpatient rehabilitation three weeks post stroke.

Over a period of 20 months, 15 patients were included. Two patients dropped out: one patient suffered a second stroke one month after the first stroke and one patient never attained any walking ability within 48 weeks post stroke. The remaining 13 patients included 7 men and 6 women. Average age \pm standard deviation (SD) was 59.4 ± 12.7 years (range, 35-79y). For comparison purposes 16 healthy control subjects (8 men, 8 women) volunteered. Average age of the control group was 61.3 ± 11.1 years (range, 33-77y). None of the control subjects had a history of motor disability, vestibular disorder, or neurological damage that would have interfered with the aims of the present study. The study was approved by the hospital's ethics committee and an informed consent was obtained from each participant.

Procedure and materials

At 3, 6, 12, 24, and 48 weeks post stroke (T_1 up to T_5) patients' motor function and, if possible, gait characteristics were assessed. Motor function was assessed with the RMI and the FAC. Gait analysis, however, did not begin until a patient was able to walk several meters independently. The use of an assistive device was allowed. Gait analysis was conducted while patients walked at a self-selected, comfortable speed across the floor of an 8x4m gait laboratory. Patients were asked to walk from one side to the other side of the lab and back, resulting in two walking cycles. In the control group, gait characteristics were assessed once.

Knee angle was measured with Penny & Giles goniometers. Piezoelectric gyroscopes were used to record angular velocity in the sagittal plane of the thigh and pelvis. Temporal parameters, used for normalizing kinematic data (heel-strike, toe-off, mid-stance, mid-swing), were recorded by means of an ultrasonic motion analysis system.¹⁷ Data were sampled at 200 Hz and further processed on a personal computer using Matlab, version 5.3.

Data analysis

Kinematics were calculated for each stride of both walking cycles and then averaged. The first and last strides of each cycle were omitted from analysis. Maximum knee flexion during swing can be used to quantify abnormalities in

knee flexion patterns.^{15,18} However, typical of a stiff-knee pattern, which often occurs in a hemiplegic gait, is the decrease in flexion *amplitude*, while a constant flexion during the full stride cycle may still be present. Therefore, we introduced the difference between knee flexion at mid-swing and mid-stance (Dknee) to quantify abnormalities in knee flexion patterns. It was expected that Dknee would be especially sensitive for revealing a stiff-knee pattern. Thigh and pelvis angle were obtained by integrating the angular velocity signals from the piezoelectric gyroscopes. An integration procedure always introduces an unknown constant in the output signal. As a result, the absolute values of the thigh and pelvis angle are arbitrary, but the shape and amplitude of the calculated signals are valid. Reduced hip flexion and extension can be compensated by sagittal rotation of the pelvis. To quantify this compensatory pelvis rotation, we calculated the difference between pelvis angle in the sagittal plane at heel-strike of the hemiplegic side and heel-strike of the non hemiplegic side (Dpelvis). In a symmetric gait pattern, the value of Dpelvis should be about zero, since the pelvis angle in the sagittal plane at heel-strike left equals the angle at heel-strike right.

The FAC and RMI were used to classify whether a patient's gait had functionally recovered. Minimum scores of 4 on the FAC and 8 on the RMI were required for a patient to be classified as functionally recovered.

Statistical analysis

To determine whether the patients group scores on the FAC and RMI improved in time a repeated measures analysis of variance (ANOVA) with one within-subjects factor [measurement] with 5 levels [T₁ to T₅] was performed. If justified, post hoc median tests on Dknee, Dpelvis and hip rotation amplitude in the sagittal plane (Ahip) were performed between patients (sub-) groups and the control group. A reduced knee flexion would result in a decreased Dknee and a reduced hip flexion and extension in a decreased Ahip. Therefore, Dknee and Ahip were tested single sided, knowing that in a hemiplegic gait pattern these variables will be lower than normal.

RESULTS

Table 1 shows mean, standard deviation and minimum and maximum values of the comfortable walking speed (Speed) for the control group. Furthermore, the difference between knee flexion during mid-swing and mid-stance (Dknee) and hip rotation amplitude in sagittal plane (Ahip) are shown, as is the difference between pelvis angle in the sagittal plane at heel-strike left and heel-strike right (Dpelvis).

Table 1. Healthy control subjects.

Variable	mean	sd	min.	max.
Speed (m/s)	1.24	0.095	1.08	1.42
Dknee (°)	38.0	2.13	33.2	44.6
Ahip (°)	46.5	3.86	40.3	53.7
Dpelvis (°)	0.1	1.46	-2.7	3.0

The mean comfortable walking speed of the patients group at T₅ was 0.81±0.43 m/s. Five patients used a walking cane and two patients required the use of an ankle-foot orthoses during the experiment. Seven patients did not need an assistive device while walking.

RMI and FAC scores

Figure 1 shows the mean group scores on both the RMI and the FAC for each measurement. Both tests showed a significant main linear effect for measurement [$F_{\text{RMI}}(1,12)=34.4, P<0.001$; $F_{\text{FAC}}(1,12)=29.3, P<0.001$].

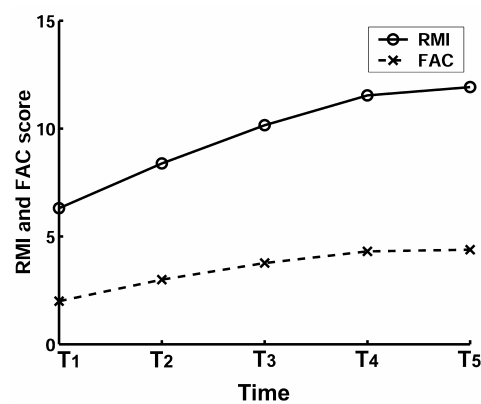


Figure 1. Mean group score on Rivermead Mobility Index and Functional Ambulation Categories for each measurement.

Dknee

Dknee is presented for each patient and for each measurement in Figure 2. Visual assessment of the hemiplegic side of Figure 2 clearly reveals two subgroups. In a subgroup of seven patients in the upper part of the figure, Dknee recovered to values at T₅ close to the control group. In a subgroup of six patients in the lower part of the figure, Dknee was low and did not recover. A median test at T₅ showed a significant difference between the subgroups ($P=0.010$; single sided). Furthermore, median tests showed that the subgroup in which Dknee recovered did not significantly differ from the control group ($P=0.097$; single sided), while the subgroup that did not recover did significantly differ from the control group ($P=0.018$; single sided).

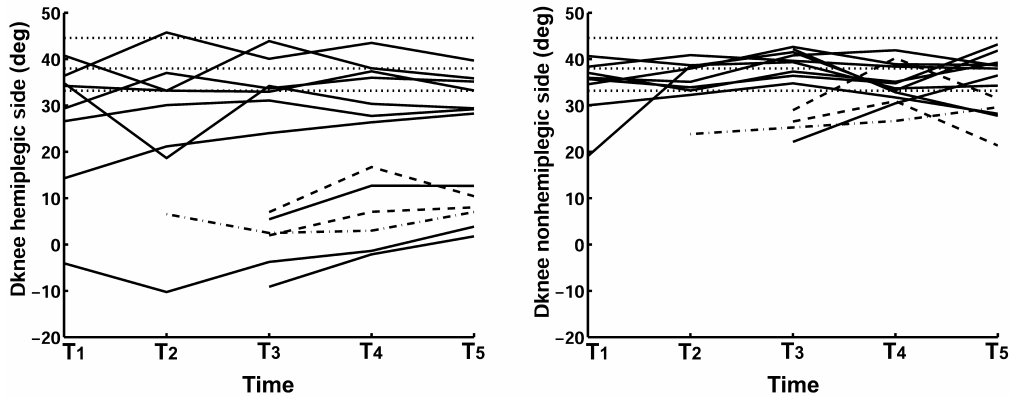


Figure 2. *Dknee*, the difference between knee flexion during mid-swing and mid-stance, presented for each patient and each measurement. Solid lines represent patients whose gait had functionally recovered at T₅ according to the FAC (score ≥ 4) and RMI (score ≥ 8). Non-solid lines represent patients whose gait had not functionally recovered at T₅: dashed lines = FAC < 4, RMI ≥ 8; dash-dotted lines = FAC < 4, RMI < 8. The dotted, straight horizontal lines represent the mean, minimum and maximum *Dknee* value of the control group.

Figure 3 shows the mean knee angle profiles for each patient. Based on both the joint angle profiles and the value of *Dknee* in Figure 2, the gait of patients in which *Dknee* had not recovered at T₅ can all be classified as a stiff-knee gait at T₅.

Dpelvis

Dpelvis is presented for each patient and for each measurement in Figure 4. Visual assessment of *Dpelvis* did not reveal different subgroups at T₅ as clearly as it did with *Dknee* in Figure 2. Therefore, patients with a *Dpelvis* within the range of the control group were classified as subjects with a recovered *Dpelvis* and patients with a *Dpelvis* outside the range of the control group were classified as subjects with a *Dpelvis* that had not recovered.

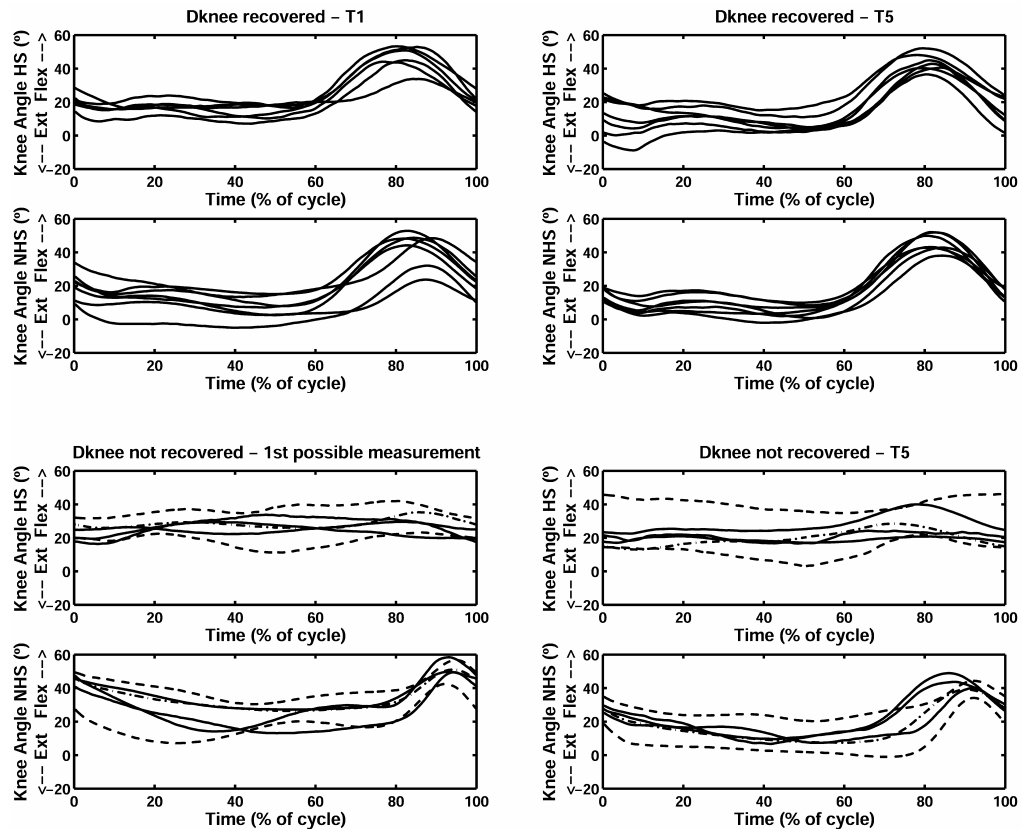


Figure 3. Mean knee angle profiles for each patient at T_1 , or first possible measurement, and T_5 . Both hemiplegic side (HS) and non hemiplegic side (NHS) are presented. The upper part of the figure shows the profiles of patients whose Dknee had recovered at T_5 ; the lower part of the figure shows the profiles of patients whose Dknee had not recovered at T_5 . Knee angle profiles at T_5 of patients whose Dknee had recovered closely resembled profiles of healthy controls. Legend: see Figure 2. Abbreviations: Ext, extension; Flex, flexion.

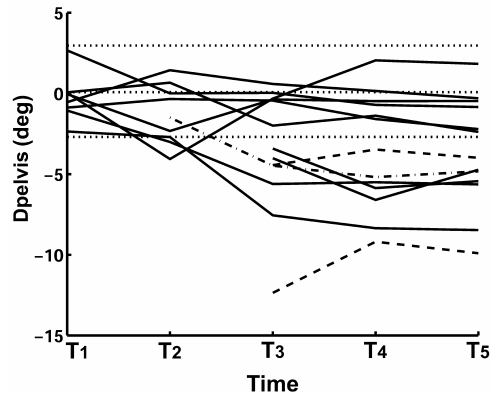


Figure 4. *Dpelvis*, the difference between the sagittal pelvis angle at heel-strike of the hemiplegic side and heel-strike of the non hemiplegic side, presented for each patient and each measurement. Legend: see Figure 2. The dotted, straight horizontal lines represent the mean, minimum and maximum *Dpelvis* value of the control group.

Figure 5 shows the mean hip and pelvis angle profile in the sagittal plane for each patient. Median tests showed a reduced hip angle amplitude (A_{hip}) on the hemiplegic side in patients whose *Dpelvis* had not recovered when compared with patients whose *Dpelvis* had recovered ($P=0.015$; single sided), and compared to healthy controls ($P=0.035$; single sided). Patients whose *Dpelvis* had recovered did not significantly differ from controls ($P=0.318$; single sided). The pelvis angle in Figure 5 clearly shows that the large negative values of *Dpelvis* at T_5 in Figure 4 reflect a pendulum pelvis movement: the lower part of the pelvis is rotated forward at heel-strike of the hemiplegic side and it is rotated backward at heel-strike of the non hemiplegic side.

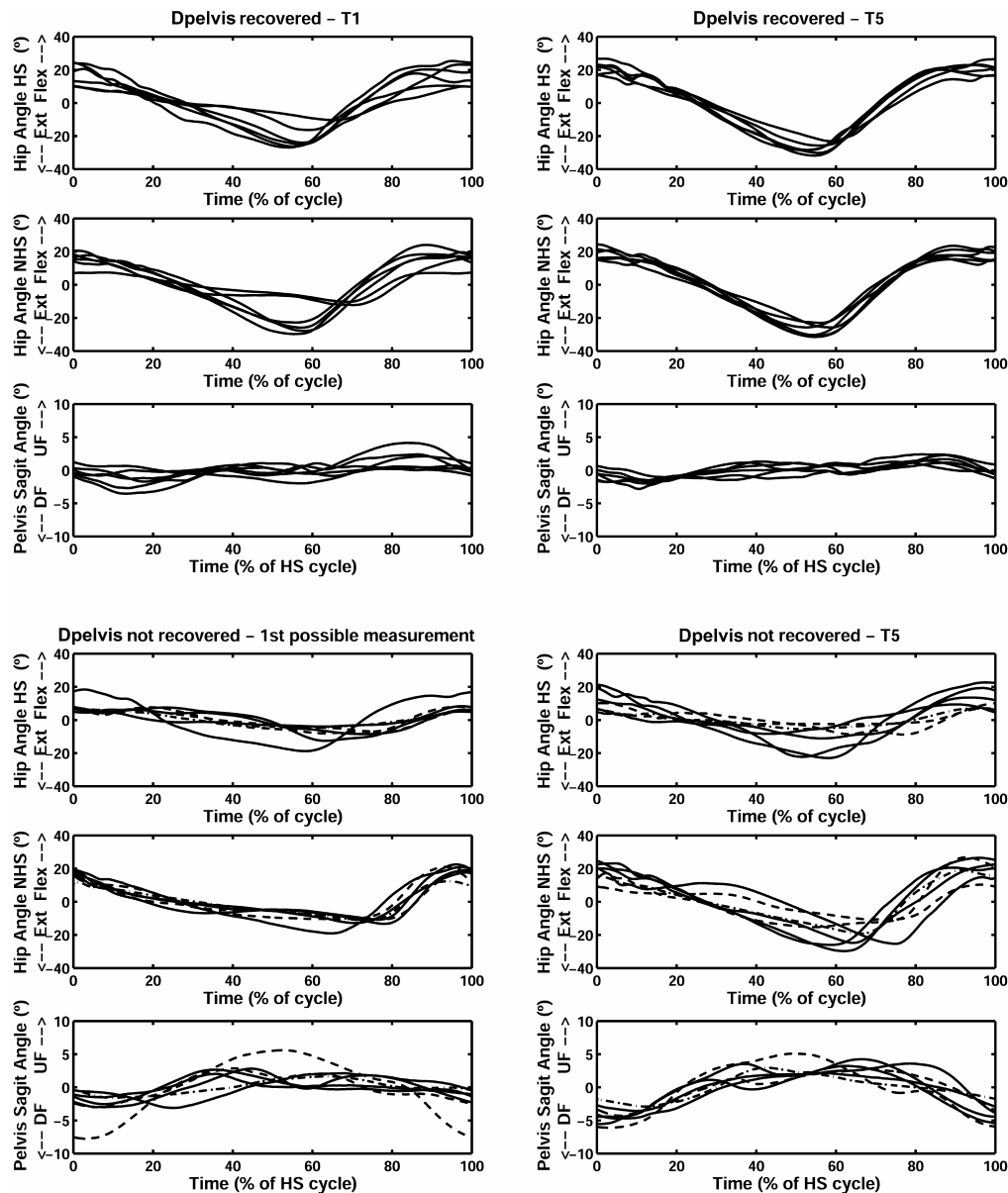


Figure 5. Mean hip and pelvis angle profile in the sagittal plane for each patient at T_1 , or first possible measurement, and T_5 . Both hemiplegic side (HS) and non hemiplegic side (NHS) of hip angle are presented. Positive values for pelvis angle denote rotation of the upper part of the pelvis forward (UF); negative values denote rotation of the lower part forward (DF). Pelvis rotation is normalized according to a cycle of the hemiplegic side (heel-strike HS to heel-strike HS). The upper part of the figure shows the profiles of patients whose Dpelvis had recovered at T_5 , the lower part of the figure shows the profiles of patients whose Dpelvis had not recovered at T_5 . Hip and pelvis angle profiles at T_5 of patients whose Dpelvis had recovered closely resembled profiles of healthy controls. Legend: see Figure 2.

DISCUSSION

Maximum knee flexion during swing is often used to quantify abnormalities in knee flexion patterns^{15,18} so that a spastic paretic stiff-legged gait is defined as reduced knee flexion during swing.^{19,20} However, typical of a stiff-knee pattern is the decrease in flexion *amplitude*, while a constant flexion during the full stride cycle may still be present. The lower part of Figure 3 shows that, for some patients, maximum knee flexion during swing of the hemiplegic side reached values close to values in a healthy gait pattern, while at the same time the amplitude of the signal was far from normal. Therefore, maximum knee flexion during swing is not suitable for revealing a stiff-knee pattern. In the present study the difference between knee flexion at mid-swing and mid-stance (Dknee) was used to quantify a stiff-knee gait. It appears that this parameter is quite sensitive for detecting a stiff-knee gait. Since no EMG recordings were made, the stiff-knee gait patterns cannot be classified with full certainty as spastic paretic stiff-legged gait, but it is likely that Dknee is more sensitive in detecting a spastic paretic stiff-legged gait than the maximum knee flexion during swing.

From Figures 2 and 3 it can be concluded that when no stiff-knee gait is present after stroke, patients' gait will also functionally recover. Absence of a stiff-knee gait is not, however, a requirement for functional recovery since three patients with a stiff-knee gait also showed functional recovery. The question arises whether a stiff knee may be functional or, to go even further, would these three patients have recovered walking in a functional sense when no stiff knee had developed? Several mechanisms have been proposed as a cause of stiff-knee gait. Spasticity of mainly the quadriceps was long considered to be the sole cause of stiff-knee gait. But recent work has indicated hip flexor weakness or poor ankle mechanisms are possible causes also.^{18,21,22} When a stiff-knee gait in a stroke patient is mainly caused by spasms, it could be the consequence of a lack of inhibition from higher cortical areas on spinal structures. However, we argue here that a stiff knee may emerge also as a result of a compensatory strategy due to cortical lesions having destroyed the smooth exploitation of motor programs required for normal gait. In order to optimize the output, the brain constructs a

second best option in that a novel motor strategy (program) develops that enables the patient to support his weight during single support on the hemiplegic side and regain functional walking ability. This principle of output optimization on the basis of a novel strategy is an emergent characteristic of the neural system that has clear survival value.^{23,24} Nevertheless, why did three stiff-knee gait patients show functional recovery while three others did not? Part of the answer to this question may be found in radiological or clinical differences between subjects, e.g. the more severe the stroke, the less chance of functional recovery. These variables were not included in the experimental design as independent variables, however, and were therefore insufficiently recorded to be part of a post hoc analysis. Location and type of stroke did not, however, appear to differ between these patients and neither did the use of an assistive device during walking.

Figure 2 shows that development of a stiff-knee gait can be predicted by D_{knee} at the first possible gait analysis: if D_{knee} is below 10° it will not reach a normal value and a stiff-knee gait will develop. However, when a stiff knee can be functional, early recognition may be valuable for rehabilitation as in some cases it might be favourable to train the patient in using his stiff-legged gait rather than trying to change the gait towards a normal, symmetrical gait.

We used the difference between pelvis angle in the sagittal plane at heel-strike of the hemiplegic side and heel-strike of the non hemiplegic side (D_{pelvis}) to quantify possible compensatory pelvis rotation due to a reduced hip flexion and extension. For healthy subjects with a normal gait pattern, D_{pelvis} should be about zero degrees, which was indeed the case. Furthermore, all patients whose D_{pelvis} recovered within the range of the controls showed hip rotation amplitudes (A_{hip}) within the normal range. Patients whose D_{pelvis} did not recover, however, showed a significantly smaller hip rotation amplitude on the hemiplegic side. The lower right part of Figure 5 shows that the divergent values of D_{pelvis} indicated a pendulum movement of the pelvis that compensates for the reduced hip rotation on the hemiplegic side: the lower part of the pelvis is rotated forward during flexion of the hip and backward during extension.

All patients whose Dpelvis recovered, and who thus had no pendulum movement of the pelvis and a sagittal hip rotation amplitude within the normal range, showed functional recovery of gait. However, four patients whose Dpelvis did not recover, also showed functional recovery. Therefore, the recovery of Dpelvis, indicating a normal pelvis rotation and a hip rotation amplitude within the normal range, is not a requirement for functional recovery of gait. Since the pendulum movement of the pelvis in these patients appears to be a compensation for a reduced hip rotation, it is of course not unexpected that functional recovery is possible. For these patients, it may even be a requirement for functional recovery. Again, the question arises whether, in some cases, it would not be favourable to train a patient to use a pendulum movement of the pelvis rather than trying to change their gait towards a normal, uncompensated gait. In this experiment the compensatory pelvis rotation could not be predicted in an early phase as it could with the stiff-knee gait. However, supportive training once this type of gait develops might still show promise. As with “stiff-legged gait training”, more research is needed to explore which cases might benefit from such a supportive training.

CONCLUSION

Recovery of joint kinematics in hemiplegic stroke patients towards a normal pattern is not a requirement for functional recovery of walking ability. Presence of a stiff-knee gait and a pendulum movement of the pelvis do not always impede functional recovery of walking ability. In some cases, the abnormal gait patterns may even be a compensatory or adaptive strategy that facilitates functional recovery. Early recognition of these compensatory walking patterns may have implications for rehabilitation programs. The question arises whether physical therapy for these patients should aim at changing their gait towards the normal pattern. It is with necessary modesty argued that a training focused on the use of the compensatory pattern may be indicated here.

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