Recovery of standing balance in patients with a supratentorial stroke

Mirjam de Haart

de Haart, Mirjam

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Recovery of standing balance in patients with a supratentorial stroke

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Mirjam de Haart

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Promotores:

Prof. Dr. A.C.H. Geurts
Prof. Dr. J.E.J. Duysens

Manuscript commissie:

Prof. Dr. M.J. Zwarts
Prof. Dr. T.W. Mulder (Rijksuniversiteit Groningen)
Prof. Dr. F. Nollet (Universiteit van Amsterdam)

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CONTENTS

1

Introduction

'I repeatedly tried to stand up but it was impossible. I kept falling down'

(L. Bissell, 2004)[1]

Stroke is a sudden disruption of the blood flow to the brain caused by ischemia (thrombolic or embolic) or, less frequently, by haemorrhage[2]. Depending on the location of the disruption, different cerebral functions can be disturbed, leading to temporary or permanent disabilities. In the Netherlands approximately 1,75 ‰ (i.e., 28.000 inhabitants) of the total population suffer from a stroke each year and with the ageing of the population this number is expected to increase[3]. The risk of stroke increases with age, especially in patients older than 64 years, in whom 75% of all cerebrovascular accidents occur[4]. A recent 6 month follow-up cost-effectiveness and resource allocation study in the Netherlands showed that 18% of the patients who had suffered a stroke died in the hospital, 40% were discharged back home, 31% to a nursing home, 9% to a rehabilitation centre, whereas 2% remained in the hospital of admission for the total follow-up period[3]. A majority of the survivors from stroke suffer from a combination of physical and psychological impairments leading to restrictions in their capacity to perform basic activities of daily living (ADL)[5]. Of all possible sensorimotor consequences of stroke, impaired postural control probably has the greatest impact on ADL independence and gait[6]. It also shows a high correlation with perceived disability[7] and is responsible for a high incidence of falls as a major health problem in individuals with stroke[8].

Efferent control of posture The term 'postural control' is used for the control of the body position in space for purposes of orientation and stability[9]. A body is considered stable, or in balance, at a particular point in time when the center of mass (COM) can be maintained over its base of support (BOS) in both static and dynamic conditions. In dynamic conditions, such as walking, this definition takes into account the momentary velocity of the COM, because of which the COM may be temporarily outside the BOS. The COM is the virtual centre of the total body mass, determined by the weighted average of the COM of all body segments. The BOS in an erect standing position is usually defined as the area under the feet in touch with the ground and the area in between these points of contact[10]. During movements of the standing body, the vertical projection of the COM may reach the stability limits, approaching the boundaries of the BOS leading to potential instability. To maintain a stable stance position in the sagittal plane, the COM can be relocated over a fixed BOS by using so-called 'ankle' or 'hip' strategies[11-13]. Ankle strategies are commonly used in reaction to relatively small body perturbations while standing on a firm support surface. Successful ankle strategies require range of motion in the ankle joints with the feet in a foot flat position as well as sufficient strength in the lower leg muscles acting across the ankles. In the case of external perturbation, a body's forward motion is decelerated or reversed by a synergy of muscle activity that starts in the calf muscles and ascends through the hamstrings to the paraspinal muscles. A backward motion is counteracted by a similar synergy that starts in the tibialis anterior muscle and ascends through the quadriceps to the abdominal muscles[11-13]. Using the ankle strategy, the body behaves as if it were stiff allowing rotation mainly at the ankle joints ('inverted pendulum'). If the body perturbation is too large or the support surface too soft to generate sufficient vertical ground reactive force for effective use of an ankle strategy, the hip strategy is called into play[13]. A forward motion is then controlled by sequential activation of the abdominal and quadriceps muscles and a backward motion by sequential activation of the paraspinal and hamstring muscles, with the lower leg muscles relatively still, in an attempt to change the configuration of the standing body and bring the COM back over the BOS. If the body perturbation is still too large or the support surface too slippery to generate sufficient horizontal ground reaction forces (shear forces) for effective use of a hip strategy, it becomes necessary to adjust the BOS to the moving COM by taking a step[14]. Usually, such a 'stepping' strategy is selected much earlier in situations where maintenance of a fixed BOS is not considered a high priority. Moreover, although described as discrete entities, the different strategies may be used simultaneously in various mixtures to maintain postural control in the sagittal plane[13].

Postural control in the frontal plane differs from sagittal plane balance in that it is usually determined by bipedal stability. As a result, the main mechanism for controlling posture is to shift weight between the legs. This loading and unloading of the legs is primarily controlled by alternating activity of the hip abductors and adductors[15]. Only in a situation of (near) single leg stance, ankle mechanisms come into play, analogous to the above mentioned ankle strategy, however, now executed by the ankle invertors and evertors. If these mechanisms fail, a hip strategy and stepping strategy can be used in the frontal plane as well. Hence, maintaining an erect standing posture is by no means a passive activity, not even while standing unperturbed. Depending on the impact of external or internal perturbations, substantial muscle force must be generated at various body levels either for equilibrium reactions to maintain a fixed BOS or for stepping responses to adjust and redefine the BOS.

Sensory control of posture Effective postural control requires peripheral input from the visual, somatosensory and vestibular systems to detect the body's position and movement in space. Each of these senses provides different information based on a different frame of reference[16]. The somatosensory system provides static and dynamic proprioceptive as well as exteroceptive information using the physical surround as the ultimate reference frame. The visual system is designed to give static and dynamic ('optic flow') information of the body's position and movement with respect to the visual surround. The vestibulum is essentially a system of accelerometers sensitive to both linear and rotational accelerations in all planes of motion. Because the body is continuously exposed to a constant acceleration force (i.e. gravity), the vestibulum also provides information of the body's position with regard to the line of gravity. All types of postural information are continuously processed and integrated at the levels of the brainstem, the cerebellum and the cerebrum in order to monitor ongoing body movements, to compare these movements with the actions planned, to detect movement errors and to correct these errors by adjusting the motor output[17]. This mode of balance regulation is often referred to as 'feedback' control of posture. Basic research has shown that the central nervous system (CNS) is able to shift emphasis between somatosensory, visual and vestibular inputs depending on the availability and validity of sensory information. When the somatosensory and/or visual feedback are manipulated, for instance using the Sensory Organization Test (SOT) of the Neurocom Equitest System[18], healthy adults are still able to maintain standing balance[19-21]. Where one sense is not providing optimal or accurate information about the body's position and movement, the 'weight' given to that sense as a source of orientation is temporarily reduced, while the 'weight' of other, more accurate senses is increased, a phenomenon sometimes referred to as sensory 're-weighting'[22]. Thus, there is a flexible hierarchy in the CNS between different senses to maintain balance. In the case of pathology, a more systematic shift in the 'weight' of the available senses may occur. If, for instance, the somatosensory information from the legs is impaired, the visual and vestibular systems will permanently compensate for this lack of information. As for compensation by the visual system, increased 'visual dependency' becomes readily evident when such a patient is deprived of visual information. Consequently, balance problems may easily be masked if only relatively simple balance tasks would be used in clinical assessments, such as standing quietly with the eyes open[23]. Unmasking sensory deficits in the control of posture should, therefore, be pursued by challenging the body's stability using conditions of sensory deprivation or conflict[24].

Cognitive control of posture Postural control has long been considered an automatic component of human motor control, requiring little or no cognitive processing[17]. Regarding postural control as a fully automatic, 'low level' process has been gradually abandoned during the last 20 years as a result of two fundamental insights from basic research. Firstly, it was shown by several authors that the performance of secondary mental tasks during complex postural activities could cause so-called 'dual-task interference' due to simultaneous competition for limited attentional resources[25-28]. Secondly, numerous studies have shown that postural activity of the leg and trunk muscles to counterbalance fast voluntary movements of the arm occurs prior to the recruitment of the primary arm movers based on anticipation of the postural disturbance, a phenomenon which has been referred to as 'feedforward' control of posture[29-31]. Prior knowledge and expectation have a profound influence on the timing of such anticipatory postural adjustments[32-34]. Apparently, knowledge of body dynamics and task requirements can be internalised based on motor learning to control posture during movement. The use of such knowledge implies at least some cognitive processing for postural control in healthy subjects, although discontinuously rather than continuously[24]. As a result, feedforward control of posture will not easily lead to interference with a concurrent mental task. In the case of pathology, even a simple balance task may become attention demanding, when normal muscular synergies and postural strategies are disrupted, leading to dual-task interference. Therefore, clinical assessments of balance should incorporate dual-task conditions using secondary mental tasks to assess a potential loss of automaticity of standing balance, which would otherwise remain unnoticed[24].

Standing balance after stroke The functional consequences of stroke may depend on various factors including the location and size of the brain lesion[35]. In the case of supratentorial stroke, both lesions of the motor, sensory or sensori-motor association cortices and lesions of the ascending and descending neurons that connect these brain areas with the spinal cord can potentially lead to postural control deficits. Weight-bearing asymmetry and increased postural sway during normal standing have typically been observed in patients with both right and left cerebral hemisphere lesions[36-42]. During bipedal standing, such patients tend to reduce the weight that they bare spontaneously on their contralateral paretic leg, which may be related to muscle weakness, in particular loss of knee stability, as well as to somatosensory impairment of this leg. In addition, a decreased stretch reflex threshold, increased muscle tone and secondary changes in the passive muscle properties may lead to altered leg posture (usually characterised by a dominant 'extension synergy') and mechanical constraints. For instance, due to spastic pes equinus and knee hyperextension, adequate leg and foot loading may be difficult[36]. Lastly, higher perceptual deficits, such as hemineglect, may impair contralateral body awareness and, thus, the degree of spontaneous loading on the contralateral leg. Essentially the same biomechanical and pathophysiological factors may account for the impaired execution of equilibrium reactions through the paretic leg in quiet stance, leading to excessive body sway[43,44]. Furthermore, in response to both internal (self-initiated) and external perturbations, muscular activity at the paretic side of the body can be absent or delayed causing severe imbalance after stroke[45,46]. In walking, a stable erect posture must be maintained while the body is continuously subjected to internal perturbations, which requires well timed and parameterised weight shifts between the legs. Because voluntary weight shifting can be impaired in patients with stroke[47,48], gait disability will be an inherent consequence not only of impaired automatic equilibrium reactions, but also of voluntary postural control deficits.

The scope of this thesis: standing balance recovery from supratentorial stroke It is well known that patients with stroke have a substantial potential for functional recovery. Most of the survivors from stroke return to their homes within six months post onset with an ability to ambulate and to perform their basic ADL independently[3]. Recent studies have shown that such functional recovery can be partly ascribed to neural plasticity leading to recovery of elementary functions[49]. However, even without such recovery of function, patients may show increased independence in their ADL performance by learning compensatory mechanisms. As for standing balance after stroke, only very little information was available at the beginning of 1999, focusing on recovery characteristics. Yet insight in the underlying mechanical and physiological determinants of standing balance recovery seemed essential to identify and develop effective rehabilitation strategies for patients with stroke. A few longitudinal studies had been published[36,38-40] that suffered from major loss to follow up or from rather limited and sometimes biased balance assessments. Hence, it was considered appropriate to further explore standing balance deficits in stroke and to unravel which mechanisms would be responsible for subsequent balance recovery, irrespective of the extent to which this recovery would be influenced by rehabilitation. For this purpose, a dual-plate force platform was used to assess spontaneous weight-bearing, active weight shifting and several characteristics of body sway control while standing in different conditions, with special emphasis on asymmetry measures. The target population was restricted to patients with a supratentorial stroke, being the most frequent and relevant population for rehabilitation. Furthermore, eligibility of subjects was limited to patients who had been admitted in a rehabilitation centre in order to ensure that standing balance deficits would be considerable in most of the eligible patients and to be able to anticipate a minimal loss to follow up. Age-matched healthy subjects were assessed using the same procedures to obtain reference values that would control for the influence of ageing on the observed balance characteristics in patients with stroke.

Research questions

This thesis is built up of 5 main chapters, each of which addresses a specific research question.

1. What is known in the literature about the mechanical and physiological mechanisms underlying standing balance recovery from stroke?

Chapter 2 reviews scientific studies published in the medical and paramedical literature dealing with the recovery of standing balance following stroke. This review is subdivided into five major sections focusing on unperturbed stance, stance perturbations, voluntary weight displacements, sensory control and cognitive control of posture, respectively. Established pathophysiological and clinical insights as well as 'blind spots' in the existing literature are highlighted and reviewed in the general discussion.

2. Which static and dynamic aspects of the control of quiet standing are likely to underlie functional recovery of balance following stroke?

Chapter 3 identifies and interrelates static and dynamic characteristics of the restoration of the control of quiet standing in various conditions with different sensory and cognitive demands. Balance assessments are made in an inception cohort of 37 rehabilitation inpatients at five times over a period of 12 weeks, starting individually from the moment each patient was able to stand unassisted for 30 seconds. The possible influence of various biological and clinical patient characteristics on standing balance recovery is determined.

3. How does the capacity to voluntarily displace body weight recover following stroke and to what extent is this capacity associated with the control of quiet standing?

In chapter 4, the same patients as included in the study of chapter 3 are analysed for their capacity to make quasi-rhythmic submaximal lateral weight shifts providing visual feedback of the centre of foot pressure.

Again, five balance assessments are made in a period of 12 weeks and the possible influence of various biological and clinical patient characteristics on the restoration of weight-shifting capacity is determined. In addition, weight-shifting performance is associated with selected parameters of quiet-standing control, both at the start and at the end of this follow-up period.

4. How do posturographic outcomes of quiet-standing and voluntary weight-shifting tasks relate to the dependency level of walking?

In chapter 5, the data from the same inception cohort as presented in chapters 3 and 4 are used to associate selected force-platform parameters, obtained during quiet standing and voluntary weight shifting, with the dependeny level of walking as assessed with the Functional Ambulation Categories (FAC).

To further enhance our understanding of standing balance control in patients with stroke and the potential use of visual feedback of centre of pressure movements to improve their postural stability, we posed a 5th question:

5. To what extent are patients with stroke able to use visual force feedback to control quiet standing and weight shifting compared with healthy elderly and healthy young individuals?

Chapter 6 reports upon the ability of elderly persons with and without stroke to use visual feedback of the centre of foot pressure to stabilise their posture during normal standing and to maintain such a stabilising strategy after withdrawal of this visual feedback. This ability is compared to the performance of healthy young adults. Similarly, the ability to perform visual feedback controlled weight shifts is compared between these groups as well as the stability of weight-shifting performance after withdrawal of the visual feedback.

This thesis will end with a general discussion emphasising the possibilities and limitations of the applied methods, tentative therapeutical implications and directions for future research.

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2

A Review of Standing Balance Recovery from Stroke

In press:
Alexander C.H. Geurts, MD, PhD, Mirjam de Haart, MD,
Ilse J.W. van Nes, MD, Jacques Duysens MD, PhD
Gait and Posture xxxx;xx:xxx-xxx

ABSTRACT

Recently, interest in the mechanisms underlying balance recovery following stroke has grown, because insight into these mechanisms is necessary to develop effective rehabilitation strategies for different types of stroke. Studies dealing with the recovery of standing balance from stroke are, however, limited to rehabilitation inpatients with a unilateral supratentorial brain infarction or haemorrhage. In most of these patients, stance stability improves in both planes as well as the ability to compensate for external and internal body perturbations and to control posture voluntarily. Although there is evidence of true physiological recovery of paretic leg muscle functions in postural control, particularly during the first three months post-stroke, substantial balance recovery also occurs in patients when there are no clear signs of improved support functions or equilibrium reactions exerted through the paretic leg. This type of recovery probably takes much longer than 3 months. Apparently, mechanisms other than the restoration of paretic leg muscle functions may determine the standing balance recovery in patients after severe stroke. No information is available about the role of stepping responses as an alternative to equilibrium reactions for restoring the ability to maintain upright stance after stroke. The finding that brain lesions involving particularly the parieto-temporal junction are associated with poor postural control, suggests that normal sensory integration is critical for balance recovery. Despite a considerable number of intervention studies, no definitive conclusions can be drawn about the best approach to facilitate the natural recovery of standing balance following stroke.

INTRODUCTION

Stroke is one of the major causes of permanent disability with an incidence of approximately 1,75 ‰ per year[1]. Although approximately two thirds of the affected patients are above 65 years, a stroke may occur at all ages, even in very young children, and can have many causes[2]. A majority of the survivors from stroke have a combination of sensory, motor, cognitive and emotional impairments leading to restrictions in their capacity to perform basic activities of daily living (ADL)[3]. Of all possible sensorimotor consequences of stroke, impaired postural control probably has the greatest impact on ADL independence and gait[4-7]. In addition, among many biological and functional characteristics, postural control is the best predictor of achieving independent living[8] and shows the highest correlation (r_p=0.70) with person-perceived disability after discharge from rehabilitation[9]. Loss of postural control has been recognised as a major health problem in individuals with stroke resulting in a high incidence of falls both during rehabilitation and thereafter, particularly in those patients with both motor and sensory deficits[10-12]. Rapid and optimal improvement of postural control in patients with stroke is, therefore, essential to their independence, social participation and general health. However, no general physiotherapy approach has proven to be superior for promoting balance recovery from stroke[13]. There is also limited evidence of the effectiveness of sensory stimulation by acupuncture or transcutaneous electrical nerve stimulation[14], functional electrical stimulation[15], electromyographic feedback[16,17], force feedback[18] or body-weight supported treadmill training[19] on balance and related ADL inpatients with stroke.

It is necessary to have optimal understanding of the potential mechanisms underlying 'natural' balance recovery and compensatory mechanisms to provide interventions to improve the speed and extent of balance recovery following stroke. The site of the brain lesion will also affect the type and extent of postural reorganisation after stroke. This review focuses on studies using instrumented methods to obtain quantitative information about sensory, motor and cognitive processes involved in the recovery of postural control from stroke.

UNPERTURBED STANCE

Although many survivors from stroke regain the ability to stand unsupported during the first days post-onset[20], approximately 50% of the patients with a total anterior circulation infarction will not have reached independence 6-9 weeks after stroke onset[20-22]. Maintaining an unperturbed two-legged standing position, a simple task for healthy individuals, may be quite an achievement for individuals with stroke who need prolonged inpatient rehabilitation care. Once they are able to maintain standing balance, weight-bearing asymmetry in favour of the nonparetic leg as well as increased spontaneous postural sway, most prominently in the frontal plane, are among the most characteristic consequences of incompletely recovered hemiparesis[23-29]. Improvement of weight-bearing symmetry is traditionally regarded as a primary goal in rehabilitation[28,30,31] and has been associated with better motor functioning and greater ADL independence in the post-acute phase of stroke[28].

Many studies of unperturbed stance in individuals with stroke have used force-plate technology to assess weight bearing and sway characteristics based on positional and movement characteristics of the 'centre of pressure' (COP) of the ground reaction forces. The COP data so obtained, however, reflect not only actual body sway, but also the stabilising moments of force exerted through the lower leg muscles active about the ankle joints ('ankle mechanisms')[32]. As shown after strokes, increased COP movements during quiet standing seem partly related to increased body sway as assessed with kinematic recordings of the lower legs and pelvis[33] and partly to exaggerated corrective ankle mechanisms as assessed by analysing the higher frequency COP components (>0.4Hz)[34]. The ecological validity of such 'static' posturography may be questioned in view of the dynamic complexity of postural control in daily life. Yet, several studies of patients with stroke have demonstrated moderate to high associations of selected force-platform parameters derived from quiet-standing registrations, in particular the mean COP velocity, with several functional measures of balance[35-39] and gait[29,39] in both the post-acute and chronic phase (r ranging from -0.52 to -0.91). Hence, equilibrium control during the 'simple' act of standing still can explain on average 50% (r^2) of the variance of several functional balance and gait measures in patients with stroke.

Recovery characteristics One of the first studies to address balance recovery from stroke was published by Sackley[31], who investigated 90 inpatients, all participating in a regular rehabilitation programme, from the moment they were able to stand independently for 30 s. Balance was assessed on average 11.5 weeks after stroke as well as 18 weeks later. Small but significant improvements in absolute weight bearing (2-4% of body weight) were found and a relative reduction (7-30%) in the variability of weight bearing as a measure of lateral stability. A major problem of this study was the drop out of 21 patients from the first to the second assessment, making these assessments invalid for comparison. Mizrahi et al.[26] reported a trend towards spontaneous sway reduction in 16 post-acute patients with stroke during 15 weeks, but in this study only six patients were followed for at least 10 weeks making their regression analysis suspect. Sackley and Lincoln[40] found even greater improvement of absolute weight bearing (11% of body weight) and lateral stability (40%) in a study with 26 patients over a time period of 4 weeks on average 20 weeks post-stroke. Accordingly, Dickstein et al.[25] reported improved loading on the paretic leg (9.7%) during a 3-week follow up of 23 post-acute inpatients with stroke. In both of the latter two studies, however, patients were probably aware of the fact that loading symmetry was an important outcome, which may have caused measurement bias. More recently, Laufer et al.[22] followed a cohort of 104 patients with a first stroke in the anterior brain circulation who had been admitted to a geriatric rehabilitation centre. Balance was first assessed 3-6 weeks post-stroke (average 26 days) and re-assessed 6-9 weeks (average 53 days) later. In the 30 patients in the sample whose standing balance could be assessed twice, small and insignificant reductions in weight-bearing asymmetry and postural sway (RMS COP amplitude normalised to body weight) were found, even though they still exhibited substantially more weight-bearing asymmetry and higher sway values at the second assessment compared to age-matched healthy control subjects. The same group, however, recovered considerably in terms of independence in walking and ADL.

In contrast, other studies have found significant improvement of postural stability in the post-acute phase of stroke[41,42]. In a study without differential effects of force-feedback training, Walker et al.[42] included 46 inpatients on average 5-6 weeks after their first stroke, who had been admitted to a stroke unit for rehabilitation and were able to stand unassisted for at least 60 s. They were all reassessed on average 5 weeks later with functional measures of balance and gait (Berg Balance Scale, Timed Up & Go Test, gait velocity) as well as by posturography. All functional measures improved considerably, which coincided with a 45% decrease in the sway area relative to the theoretical limits of stability, both with eyes opened and closed. One month after the intervention period, the sway values had decreased further by another 25%. De Haart et al.[41] followed 37 inpatients during their rehabilitation starting from the time they were able to stand independently for at least 30 s, on average 10 weeks post-stroke, and then 2, 4, 8 and 12 weeks later. A dual-plate force platform was used to determine weight-bearing asymmetry and postural instability (RMS COP velocity). During the rehabilitation period, the patients clearly improved their independence of walking (increase in median Functional Ambulation Categories score from 2 to 4 [range 0-5]) and showed a gradual decrease in lateral (33%) and AP (18%) postural instability. Weight-bearing asymmetry decreased from 13.5% to 10% overloading on the non-paretic leg, with the greatest amount of change noted during the first 4 weeks.

Hence, a substantial degree of weight-bearing asymmetry persisted during the 8 weeks thereafter, most prominently in a subgroup of patients with disturbed sensibility or ankle clonus. Patients also showed abnormal static forefoot and lateral foot edge loading on the paretic side ('pes equinovarus') as well as substantial asymmetry in the kinetic regulation activity of each leg, without clear signs of restoration of these abnormalities (Fig. 1).

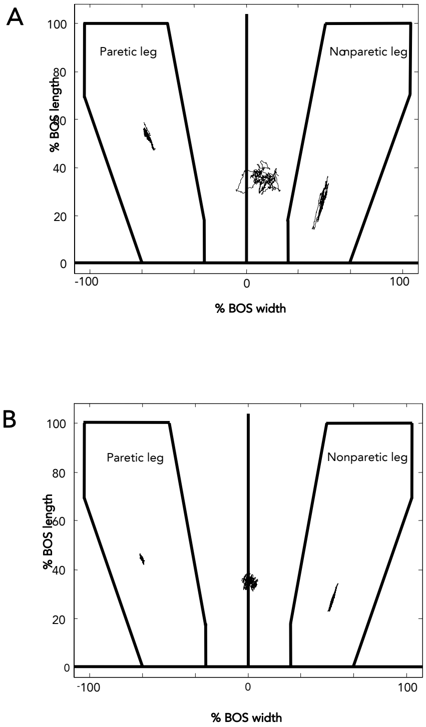

Figure 1. The COP trajectory for each foot separately and for both feet together ('overall COP') during unperturbed standing with eyes open for 30 s in a 48-year old male, who had sustained an infarction in the right-hemisphere 1 month before (A). Note the weight-bearing asymmetry reflected in the lateral deviation of the overall COP trajectory towards the non-paretic leg. Also note the asymmetry in terms of forefoot overloading at the paretic side and compensatory regulation activity at the non-paretic side (RMS AP COP velocity 29.8 mm/s vs. 7.9 mm/s at paretic side). After a 12-week training period (B), weight-bearing asymmetry had disappeared, but overloading of the paretic forefoot was still present. Although postural stability had improved substantially in terms of a decrease in overall COP velocity in both planes, the asymmetry in AP regulation activity was still a factor 3.75.

The analysis of kinetic regulation asymmetry was based on the comparison of the RMS COP velocity under each foot separately, which was on average twice as high in both directions on the non-paretic as on the paretic side. Asymmetry in kinetic regulation activity of the legs in patients with stroke has already been described by Mizrahi et al.[26] in terms of greater horizontal ground reaction forces in both directions under the non-paretic compared to the paretic foot. As body sway is relatively greater on the hemiparetic side, based on kinematic analysis of the lower legs and pelvis[33], the kinetic regulation asymmetry must reflect the use of compensatory ankle mechanisms generated by the non-paretic leg. Because de Haart et al.[41] found little evidence of restoration of symmetry with regard to either equinovarus loading or kinetic regulation asymmetry, the observed functional recovery and improved postural stability must, at least partly, be related to mechanisms other than the restoration of support functions and equilibrium reactions exerted through the paretic leg. Even though they included patients earlier after stroke, Laufer et al.[22] arrived at a similar conclusion, namely that improvement in ADL and gait dependence occurred in their patients without significant improvement in weight-bearing symmetry.

Effects of force feedback Shumway-Cook et al.[43] provided preliminary evidence of a beneficial effect of 'static' COP feedback on weight-bearing symmetry during quiet standing. Sixteen post-acute patients with stroke were randomly allocated to either 2 weeks physiotherapy including postural sway biofeedback or 2 weeks of conventional physiotherapy. In the feedback training group, subjects had to maintain their COP within a rectangular area displayed in the centre of a computer screen while standing upright for several minutes twice a day. No differential effects were found for postural stability ('total sway area'), but the reduction in weight-bearing asymmetry was greater in the experimental group. Besides the relatively small numbers studied per group, a further weakness of this study was that the experimental group alone received daily assessment and practice on the same equipment and task that were used for measuring the outcome of the intervention in both groups. This repeated 'exposure' to the outcome assessment might have led to biased results due to greater familiarity with the test. Lee et al.[44] also reported positive effects of 'static' COP feedback training on weight-bearing symmetry in 60 acute patients with stroke or head injury, but their results were skewed by an increasingly high dropout rate during the course of the 3-4 week training period related to 'good recovery'. Whether such training can be used to improve stance stability should be questioned seriously, because both healthy elderly persons and elderly persons with stroke are typically unable to reduce their spontaneous sway amplitude using visual COP feedback[45].

Other studies have used 'dynamic' COP feedback to improve weight bearing and postural stability. Winstein et al.[46] evaluated the efficacy of providing dynamic visual information about relative weight distribution over the paretic and non-paretic leg in 38 inpatients with stroke undergoing rehabilitation. Besides regular physical therapy, the experimental group received feedback training for 3-4 weeks, 30-45 min per day and 5 days per week. This started with normal standing and progressed from sit-to-stand transfers, to lateral and AP weight shifting, and to stepping in place. Evidence was found of improved weight-bearing symmetry during quiet standing in this group compared to the control group, that participated in extra routine standing balance and weight-shifting training. However, no differential effects were observed for postural stability (COP variability) or for various gait parameters (gait velocity, cadence, stride length and gait cycle duration). The positive result for weight-bearing symmetry may have been biased because the experimental group was much more frequently exposed to the outcome assessment than the control group. Moreover, it is unclear whether the experimental group received an equal amount of therapy compared to the control group. Sackley and Lincoln[40] conducted a randomised controlled trial (RCT) to compare the effect of a similar dynamic weight-bearing feedback protocol with a placebo programme in 26 patients who had been admitted to a hospital stroke unit on average 20 weeks post-stroke onset. They reported more improvement of stance symmetry, gross motor function and ADL in the experimental group directly after the 4 weeks of training, but these differential effects were lost after a follow up of 8 weeks. Other RCTs that investigated the effect of COP feedback training while actively shifting weight during various standing activities did not find specific treatment effects on postural stability (sway area)[42] or functional measures (Timed Up&Go Test, Berg Balance Scale, gait velocity)[18,42] in the post-acute phase of stroke. Hence, the overall evidence of a persistent or functionally relevant effect of static or dynamic force-feedback training on weight-bearing symmetry or stance stability in patients with stroke seems to be rather weak.

Effects of aids In contrast to the ambiguous results of force-feedback training on weight-bearing symmetry during quiet stance, the use of simple aids may have rather dramatic effects in this respect. The addition of a 10 mm shoe lift under the non-paretic leg resulted in a 10% increment in weight bearing on the paretic leg in eight patients in the chronic phase of stroke who bore on average 38% weight on this leg. This improvement showed a significant carry-over effect immediately after the shoe lift had been removed[47]. Such compelled weight bearing was also achieved by placing a pronating wedge under the shoe of the non-paretic leg in nine post-acute patients with stroke. A shoe wedge with an angle of just 5° resulted in a shift from 40% to 51% weight bearing on the paretic leg, whereas greater angles resulted in overloading of the paretic leg. Again, a significant carry-over effect of approximately 44% weight bearing was found immediately after removal of all wedges[48]. An even more dramatic increase in weight bearing on the paretic leg (from 41-42% to 65-68%) has been reported in post-acute patients with hemi-paresis when placing their non-paretic foot on a step, regardless of step height (10 cm or 17 cm)[23,49], although such compelled weight shifting may not directly improve gluteus medius activation at the paretic side[50]. Because none of these studies reported measures of postural stability, no conclusions can be drawn in this respect.

Others[51,52] studied the effects of a standard and quad cane on weight bearing and postural stability in 30 post-acute patients with stroke of moderate severity and found that simply using a cane on the non-paretic body side unloaded the non-paretic leg from 63% to 58% of body weight, without affecting the weight borne on the paretic leg (37%). The use of a cane also reduced the sway amplitude measured with two force plates, the quad cane being twice as effective as the standard cane. This stabilisation was most marked while standing in a staggered position with the paretic foot placed forward, probably because this stance position resulted in the largest base of support. The maximum percentage of body weight loading on the cane was approximately 5%. Maeda et al.[53] demonstrated that the use of a one-point cane can reduce the postural sway ('sway area') in patients with stroke more effectively than in healthy elderly. The use of an anterior ankle-foot orthosis (AFO), giving support to the ankle joint and the ventral side of the tibia, has been shown to increase the maximum weight loaded on the paretic leg from 54% to 61% in 24 patients in the chronic phase of stroke, without affecting postural stability[54]. Weighted garments probably have no effect on functional balance or gait in patients with stroke[55]. In conclusion, aids such as shoe adaptations or AFOs may be able to improve substantially spontaneous weight bearing, whereas canes may be able to improve both weight distribution and stance stability in individuals with stroke.

STANCE PERTURBATIONS

The ability to withstand external perturbations in an upright position is essential to the safety of standing and walking. In addition, internal perturbations caused by self-initiated movements must be counteracted as smoothly as possible to maintain balance during voluntary activities. Cross-sectional stance perturbation studies comparing patients with stroke, often in the chronic phase, with age-matched healthy control subjects have found evidence of the following: (1) a generally impaired ability to withstand external perturbations[56,57], in particular towards the paretic side[58]; (2) delayed, temporally disrupted and weakened short-latency[59] as well as medium- and long-latency[56,60-65] leg muscle responses at the paretic side in reaction to movements of the support surface; (3) delayed and reduced leg muscle activation particularly on the paretic side in anticipation of rapid, self-paced arm movements[66,67] and (4) compensatory activation of non-paretic leg muscles in reaction to movements of the support surface[61,68,69] or prior to self-initiated disturbances[67]. As a result, individuals with stroke will avoid large passive body mass displacements and rely excessively on their non-paretic leg muscles to stabilise their posture[56]. They will also limit the speed and amplitude of self-initiated movements causing internal perturbations of posture[56,66-67] compared to healthy age-matched individuals. These phenomena have been referred to as 'stabilisation' strategies[56].

Recovery characteristics With regard to the recovery of externally perturbed standing, Kirker et al.[70] were able to show changes in compensatory hip muscle activity in response to standardised sideways perturbations (2-3% of body weight) in 13 selected patients who were tested 3-15 weeks post-stroke (the moment they were able to stand unsupported) and retested 10-38 weeks later, depending on the speed of functional recovery. They found that initially 12 patients showed abnormal hip muscle activation, of whom eight gradually developed a more physiological pattern. Although most subjects improved their hip muscle recruitment within 12 weeks post-stroke, in two subjects recovery was observed even after 13 and 21 weeks. In the most severe cases, there were no responses in the hip muscles to perturbations in either direction ('pattern 1'). In the case of some recovery, the non-paretic gluteus medius became active when perturbed in this direction as well as the non-paretic hip adductor on perturbations towards the paretic side ('pattern 2'). If recovery continued further, the paretic gluteus medius became active on perturbations in this direction ('pattern 3'). Eventually, the paretic adductor became active when perturbed towards the non-paretic side ('pattern 4'). Whereas pattern 2 revealed compensatory adductor activity of the non-paretic leg, patterns 3 and 4 were regarded as evidence of true physiological recovery, which always occurred in this order. EMG latencies of the paretic gluteus shortened in seven recovering patients, but normalised only in three subjects. Of the five patients that did not show evidence of improved hip muscle responses (two with pattern 1 and three with pattern 3), functional recovery in terms of independent mobility was relatively poor. However, temporary compensatory muscle activation did not necessarily prevent recovery of physiological muscle patterns at a later stage.

Garland et al.[21] used an internal perturbation protocol and found additional evidence for compensatory activity of the non-paretic leg as a basis for functional recovery in a subgroup ('IIb') of 12 post-acute patients. These had recovered relatively slowly and reached independent standing ability on average 6 weeks post-stroke. Although this subgroup showed similar improvements of mobility and gait speed at 1 month follow up as the other 15 patients, they did not show the same significant decrease in the latency of anticipatory ipsilateral (non-paretic) and contralateral (paretic) hamstrings activation on rapid forward flexion of the non-paretic arm while standing. Instead, they merely tended to increase the activity in the ipsilateral (non-paretic) hamstrings as compensation. In contrast, the 15 patients who were less severely affected or had regained more function before the initial assessment showed a clear improvement of bilateral anticipatory hamstrings activity which could not be explained by an increase in acceleration of the flexing arm. Because these latter patients improved their anticipatory paretic hamstrings activity by at least 20 ms (on average 80 ms), this result was interpreted as evidence of true physiological recovery. Remarkably, only subgroup IIb showed a significant increase (19%) in postural stability (decrease in RMS COP velocity) at 1-month follow up, which was less obvious in the other patients, perhaps due to ceiling effects. The muscular activation pattern in this subgroup indicates that improved postural stability during internal perturbation may be related to compensatory use of the non-paretic leg muscles instead of physiological recovery of the paretic leg muscle functions. This conclusion seems coherent with 'pattern 2' responses to external perturbation reported by Kirker et al.[70].

Effects of perturbation training One study has reported beneficial effects of dynamic platform training in 13 inpatients with stroke undergoing rehabilitation compared to 11 matched control patients[71]. Only the experimental group was trained to sustain increasing amplitudes in the AP and lateral directions of a moving support surface during 10 min of daily exercise time for 3 weeks. After the intervention period this group exhibited more than a two-fold increase in the maximally sustainable movement amplitude (MMA) with the greatest improvement in those patients who were initially most impaired (five- to seven-fold improvements of MMA). In addition, the experimental group showed more improvement in stance symmetry compared to the control group. It remained unclear, however, to what extent both groups were comparable at baseline. The results may also have been biased by different intensities of treatment. The same researchers found no favourable immediate effects of laterally moving platform exercises on the asymmetric recruitment of gluteus medius or medial gastrocnemius muscles in the chronic phase of stroke[56]. Hence, definitive conclusions about the possible effects of perturbation training on dynamic postural stability in patients with stroke cannot be drawn.

VOLUNTARY WEIGHT DISPLACEMENTS

The capacity to voluntarily transfer body weight while maintaining standing balance over a fixed base of support or to actively change the base of support and adopt a different stance position is a prerequisite for safe mobility. Cross-sectional studies of the voluntary weight-shifting capacity in patients with stroke when compared to age-matched healthy control subjects have provided evidence of the following: (1) multidirectionally impaired maximal weight shifting during bipedal standing[72,73], in particular towards the paretic leg[23,74-76]; (2) slow speed, directional imprecision and small amplitudes of single and cyclic sub-maximal frontal-plane weight shifts, most prominently towards the paretic side[45,56,62,77-80]; (3) bilaterally impaired transitions from bipedal to single-limb stance due to insufficient hip muscle recruitment on the paretic side[81] or failure to maintain single-limb support, in particular on the paretic leg[82,83]; and (4) abnormal loading asymmetry as well as reduced kinetic energy and rising speed during sit-to-stand transfers[84-88]. As a consequence, patients with stroke will only use a small part of their base of support for voluntary weight displacements, which is probably compensated by the early use of change-in-support strategies or stepping responses, which appear to be relatively preserved[81].

Recovery characteristics de Haart et al.[78] studied the restoration of weight-shifting capacity in 36 patients on average 10 weeks post stroke and 2, 4, 8 and 12 weeks thereafter. Patients had to make ‘rhythmic’ lateral weight shifts using visual COP feedback from a computer monitor, on which two stationary blue squares (30 mm x 30 mm) were presented at either side of the vertical midline. The position of the squares was individually adjusted so that 65% of body weight had to be born on either leg to bring the COP in the middle of the corresponding square. Subjects had to maintain their COP within a highlighted target square for 1 s to make a ‘hit’, after which the contralateral square became the target. Subjects were instructed to make as many weight shifts as fluently as possible in 30 s (see Fig. 2).

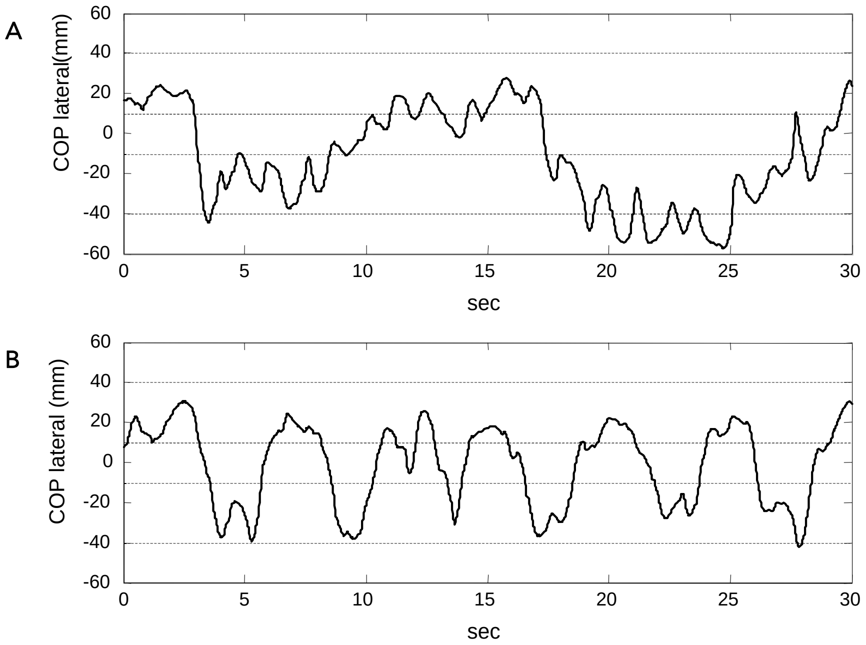

Figure 2. The lateral COP trajectory (positive values towards the right, negative values towards the left from the sagittal midline) during voluntary lateral weight-shifting for 30 s in a 65-year old male, who had sustained an infarction in the left cerebral hemisphere. The interrupted lines (at 10 and 40 mm) indicate the target positions at either side. Note that weight shifting is troublesome in both directions, but much more effective and fluent at the end of a training period (B) compared to the start of the training 12 weeks before (A).

During the first 8 weeks, patients' weight-shifting speed improved from 6.9 to 9.2 hits (33% increase) to stabilise thereafter at a level still significantly slower than that of healthy elderly. At the same time, the imprecision of weight shifting, reflected by the average lateral COP displacement per weight shift, gradually decreased by 25% and reached normal reference values after 12 weeks. During the rehabilitation period patients showed a constant asymmetry in weight-transfer time with weight shifts towards the paretic leg being 23% slower than weight shifts towards the non-paretic leg. Hence, patients with stroke increased their speed of weight shifting by a proportionate decrease in weight-transfer time towards either leg, which underscores the notion that these patients experience difficulties with weight shifting bilaterally. Nevertheless, the moderate asymmetry in weight-transfer time suggests that problems with controlling the terminal phase of a weight shift onto the paretic leg are relatively great compared to problems with initiating the beginning of a weight shift from the paretic leg or controlling the terminal phase of a weight shift onto the non-paretic leg[82,83]. Because non-paretic hip muscles can compensate for the lack of hip muscle function at the paretic side[70] and because recovery of paretic hip muscle function may occur as well[81], it is possible that the constant degree of weight-transfer time asymmetry reflects a perceptual rather than a motor problem. Indeed, patients with hemi-neglect exhibited a relatively high degree of asymmetry[78].

Effects of force feedback Ustinova et al.[89] examined the learning of voluntary weight shifts based on visual COP feedback in patients with different types of stroke in the territory of the middle cerebral artery, on average 10 months post-onset. Forty-three patients received force-feedback training on 10 consecutive days in addition to traditional rehabilitation. They first had to move their COP onto a randomly positioned target and then move this target into a designated basket. The other 39 patients only received traditional treatment. After the training period, the experimental group exhibited more reduction in weight-bearing asymmetry than the control group and more improvement of postural stability (COP velocity) when standing in a forced symmetrical position. Remarkably, these patients also showed more improvement of lower limb strength and deep sensation, which cannot easily be attributed to a 10-day weight-shifting protocol on average 10 months post-stroke. Because assessments were done unmasked, it must be considered that expectation effects may have influenced the results from the experimental group. Furthermore, no follow up of group differences was reported. Matjacic et al.[90] reported improved maximal voluntary weight-shifting capacity as well as improved spontaneous weight bearing after 2 weeks, 5 days per week, 20 minutes dynamic balance training with a special mechanical device providing both variable stabilising forces in two planes of motion and visual feedback of body movements on a computer monitor. This report, however, concerned only one patient in the chronic phase of stroke with left-sided hemi-paresis and hemi-neglect. No immediate effects of voluntary lateral weight-shifting exercises were observed on the asymmetric recruitment of gluteus medius or medial gastrocnemius muscles in the chronic phase of stroke[56].

The effects of repetitive sit-to-stand training using visual weight-bearing feedback and a postural correction mirror were investigated in a group of 54 post-acute patients with stroke. They were randomly assigned to a conventional training programme (N=24) or to the same training programme in which part of the exercises was substituted by 50 min biofeedback training (N=30) during 3 weeks, 5 days per week. In the biofeedback group, subjects were trained for standing postural symmetry and stability during 30 min per day and for symmetry of sit-to-stand movements during 20 min per day[91]. Compared to the control group, the biofeedback group demonstrated less loading asymmetry and less postural instability during body rise and a greater increase in lifting force leading to a shorter duration of body rise (respectively, 9% versus 34% improvement). These effects persisted up to 6 months after the training period, however, the influence of the force feedback cannot be distinguished from that of the visual feedback. Similar improvement of sit-to-stand performance has been demonstrated by applying strength training to the lower limbs in patients with chronic stroke. After a 12-week, two times per week progressive resistance strength training programme, Weiss et al.[92] observed a 21% decrease in repeated sit-to-stand time and a 12% improvement in functional balance (Berg Balance Scale) in seven elderly patients, living at home, on average 1 year after stroke. Hence, biofeedback training and perhaps also strength training may promote dynamic balance skills, especially during sit-to-stand transfers, in patients with stroke both in the post-acute and chronic phase.

SENSORY CONTROL

Patients in the post-acute phase of stroke tend to rely more on visual information for postural control in both planes than healthy age-matched individuals. Deprivation of vision provokes increased COP amplitudes and velocities during unperturbed standing, whereas it does not seem to affect weight-bearing characteristics[22,41]. The excessive reliance on vision for standing upright may decrease during rehabilitation[41], most prominently for frontal-plane balance, but can still be found in the chronic phase under more challenging conditions. Indeed, Bonan et al.[93] reported balance problems in a group of 40 ambulatory patients who had suffered a first stroke at least 1 year before using the sensory organization test (SOT), the protocol of the Equitest[94,95]. Significantly poorer equilibrium scores were found compared to normal reference values only when patients were standing with the eyes closed on a sway-referenced support surface (SOT 5) and, most prominently, when they experienced a conflict between visual and vestibular information while standing with both sway-referenced vision and sway-referenced support (SOT 6). Additionally, many falls were recorded in these two conditions. Several patients were able to perform relatively well during SOT 5 compared to SOT 6, suggesting excessive reliance on visual input despite intact vestibular pathways. Similar results have been reported earlier when comparing stance duration in 10 hemiparetic patients balancing on a compliant versus stable support under different sensory conditions[96]. On the other hand, when standing on a stable support, even elderly persons in the chronic phase of stroke may demonstrate a level of visual dependence for postural control comparable to that of age-matched healthy subjects[39].

It has been suggested that reduced stance duration on a compliant surface during visual deprivation in patients with chronic stroke is due to difficulty of integrating somatosensory information[96]. However, Bonan et al.[93] hypothesized that such abnormal reliance on vision may be more related to a higher-level inability to select the pertinent sensory input. The fact that they found a trend towards the poorest equilibrium scores in SOT 6 for patients with lesions of the parieto-insular vestibular cortex (PIVC) was considered to support this hypothesis, although primary somatosensory impairments were more frequent in patients with PIVC lesions. A 'simpler' explanation for the increased visual dependence in patients with stroke is a disease non-specific strategy to compensate for the loss or distortion of other sensory input[41,93]. By increasing the sway amplitude in the absence of vision, other sensory systems (particularly the vestibulum) may be able to substitute this loss of information. However, a clear relationship between the severity of somatosensory impairment and the degree of visual dependence for postural control has not yet been reported in individuals with stroke.

Effects of visual-deprivation training There is initial evidence that even in the chronic phase of stroke, training can reduce the degree of visual dependence for postural control. Bonan et al.[97] randomised 20 patients, who had suffered a first stroke at least 1 year before, to either a control group who was allowed free vision or an experimental group who was blinded with a mask throughout all sessions. Both groups received the same progressive balance exercises 1 h per day, 5 days per week, for 4 weeks. Although the groups were comparable at baseline with regard to their clinical characteristics and improved their balance performance in all six conditions of the SOT, the gain in the vision-deprived group was greater than in the free-vision group, especially in the more complex sensory conditions. This result suggest that the vision-deprived group improved their integration of somatosensory and vestibular inputs more than the free-vision group and, thus, became less visually dependent. Such an improvement even in the chronic phase of stroke underscores the notion of visual dependence being a 'learned' strategy rather than a stroke-specific impairment[97].

COGNITIVE CONTROL

Another non-specific strategy in persons with impaired postural stability is to allocate more attention to their standing balance than usually required by healthy age-matched individuals. There is ample evidence of increased

interference of postural control with a secondary attention-demanding task in older adults compared to the young, particularly in elderly with a history of falls. The degree of dual-task interference may depend on the complexity of either task[98]. It is, however, less clear to what extent such interference uniquely reflects the enhanced attention demands for motor control due to ageing (or subtle pathology) or whether it is also determined by age-related deficits of divided attention[98]. Against this background, Brown et al.[99] recently compared six patients in the chronic phase of stroke with six age-matched elderly with regard to their attention demands for static postural control. They used a simple reaction-time task in which subjects had to respond as quickly as possible with a verbal response ('top') to a visual stimulus (illumination of a light). Reaction times were recorded in both groups while sitting, standing with the feet comfortably apart and with the feet together. Only the persons with stroke showed a progressive increase in reaction times (10-15%) from sitting to standing with a narrow support base. Although this study did not compare balance performance between groups and task conditions, it was controlled adequately for possible age-related attention deficits. It has provided initial evidence of increased attention demands for standing compared to sitting balance as a consequence of stroke.
As for standing balance recovery, de Haart et al.[41] examined the influence of a concurrent arithmetic task in 37 patients in the post-acute phase of stroke. While maintaining an upright standing position for 30 s, subjects had to respond verbally with either 'good' or 'fault' to varying auditory sets of eight single-digit additions. While standing upright, the patients made the same number of arithmetic errors (25%) as when sitting. During the dual task, no consistent evidence was found of increased postural instability. However, patients reduced further the spontaneous weight loaded on their paretic leg, which was already at least 10% deviating from an equal weight distribution during quiet standing as a single task. They also increased the relative forefoot loading on the paretic side, which was already abnormal during simple upright standing. Thus, it appeared as if they were 'pushing themselves away' from stance symmetry. This effect of attention distraction on foot loading asymmetry did not diminish over the course of rehabilitation, indicating that weight bearing on the paretic leg during normal standing tends to remain under cognitive control and may not easily become 'spontaneous'.

Influence of attention deficits Considering the possible effects of attention on standing balance, it is important to recognise that attention deficits might influence the recovery of both postural symmetry and stability from stroke. Among the first to specifically address this question were Stapleton et al.[100], who tested 13 patients for attention deficits, balance impairments and incidence of falls at a median of 34 days post-stroke as well as 6 weeks later. Visual selective attention, auditory sustained attention, and auditory selective attention were examined using three subtests of the test of everyday attention (TEA). Visual inattention was assessed with the star cancellation test and balance was assessed with the Berg Balance Scale. Although high levels (46-92%) of attention deficits were found at initial assessment and seven patients (54%) showed visuospatial hemi-neglect, only auditory selective attention was associated with balance (r_s=0.67). Due to the small sample size, a possible relationship between attention deficits and falls could not be observed. It also remained unclear whether the presence of auditory selective attention deficits affected the rate of balance recovery. The same research group recently reported about the relationship between attention deficits (now also including a TEA subtest for divided attention), balance, ADL and falls in 48 community-dwelling ambulatory patients on average 46 months post-stroke[101]. In these patients moderately high levels (19 – 44%) of attention deficits were found. Only five patients (10%) showed visuospatial hemi-neglect. Both divided attention and auditory sustained attention were associated with balance and ADL (r_s=0.40 – 0.54) and fall status (r_s=-0.37 – -0.41). Despite the associations found, it remains to be elucidated whether such attention deficits may interfere with balance recovery in the post-acute phase of stroke.

Influence of hemineglect Instrumented studies of sitting balance in post-acute patients with severe stroke have demonstrated a profound negative influence of visuospatial hemi-neglect on postural stability and body orientation characterised by a contralesional tilt of the active postural vertical[102-105]. However, the influence of hemi-neglect on standing balance does not appear equally strong once patients are able to maintain an independent upright position[22,41,93,101]. Yet, some studies have indicated more severe loading asymmetry and postural instability in patients with right compared to left hemisphere lesions, most probably related to the presence of visuospatial hemi-neglect[27,88,106]. As for voluntary lateral weight-shifting capacity, post-acute patients with hemi-neglect performed 10-20% slower than those without hemi-neglect, which coincided with a relatively long weight-transfer time towards the paretic leg[78]. Because there was no influence of the severity of the primary sensori-motor impairments, the greater weight-transfer time asymmetry may have been related to slower central processing of somatosensory information while loading the paretic leg. On the other hand, relative slow processing of visual information from the corresponding side of the feedback monitor must also be considered as an explanation for the observed asymmetry, since the applied weight-shifting task requires a considerable amount of concurrent visual attention. The presence of hemi-neglect did not influence the recovery of weight-shifting capacity in terms of speed or precision[78].

DISCUSSION

Although numerous studies have identified many pathophysiological aspects of standing balance control in patients with stroke, relatively few studies have dealt with the recovery of standing balance to provide information about which of these aspects are likely to improve during the post-acute phase of rehabilitation[21,22,31,41,70,78]. Nearly all of the published longitudinal studies have focused on relatively severely affected patients with a single supratentorial brain infarction or haemorrhage who had been selected for admission in a rehabilitation centre. Although these patients are probably most relevant to clinical rehabilitation in terms of patients' needs and professional efforts required, little can be said about balance recovery in less severely affected patients with hemispheric stroke, or in those with an infratentorial stroke, e.g. of the brainstem or the cerebellum. The same is true for patients with bilateral lesions, in which one must expect very severe balance problems because the control of the trunk will be much more affected compared to patients with unilateral lesions[107,108]. Future research on standing balance recovery should, therefore, focus also on these latter types of stroke.

Even in selected patients admitted for rehabilitation, standing balance recovery from stroke may show considerable inter-individual variability, depending on the initial sensori-motor and cognitive deficits. In most of these patients, stance stability improves in both planes[31,40-42] as well as the ability to compensate for external[70] and internal[21] body perturbations and to voluntarily control posture[78]. Although there may be true physiological restoration of paretic leg muscle functions in postural control, particularly during the first 3 months post-stroke[21,70], the most striking conclusion from a perspective of neural plasticity is that substantial recovery of standing balance and related ADL occurs also in patients when there are no clear signs of improved support functions or equilibrium reactions exerted through the paretic leg[21,22,41,70]. This type of recovery probably takes place over a much longer time period than 3 months. This conclusion is corroborated by the fact that many studies investigating the possible influence of motor stage, muscle strength or spasticity of the paretic leg on static or dynamic standing balance reported relatively weak or no effects at all[21,36,41,78,89,93,109]. Apparently, mechanisms other than the restoration of paretic leg muscle functions may determine the standing balance gains in patients with severe stroke, perhaps comparable with the situation after a lower limb amputation[110,111]. One might think of improved stabilisation of the head and trunk in space, more effective muscular compensation through the non-paretic leg, adapted multi-sensory integration, progressive internalisation of the altered body dynamics, or even increased self-confidence. Future research should try to further discriminate each of these possible mechanisms as a function of stroke severity to improve individual goal setting in rehabilitation.

Trunk control Although the prognostic relevance of sitting balance after stroke is well known[112-114], longitudinal studies using instrumented analysis of sitting balance or trunk control are lacking. From cross-sectional studies of sitting balance in patients with stroke, there is evidence of bilaterally impaired trunk muscle strength during voluntary movements of the trunk[115-117] and of impaired voluntary and automatic trunk muscle activations during active movements of the trunk and limbs, respectively, most prominently at the paretic side[118-122]. As for standing balance, it has been shown that voluntary trunk extensor torque is substantially associated with the Berg Balance Scale score in the post-acute phase of stroke (r_p=0.51-0.64) at discharge from rehabilitation[123]. Nonetheless, improvement of efferent trunk control while sitting or standing as a relevant factor in balance recovery from unilateral stroke has yet to be determined. Cognitive deficits such as hemi-neglect and a biased subjective postural vertical may be equally important causes of seated postural asymmetry and instability, particularly in those patients who have not yet reached standing ability[104,105,124,125]. Reduction in hemi-neglect may, thus, lead to balance recovery, although this assumption needs to be underscored by empirical evidence as well. Of several intervention studies[126-129], only one trial[127] has demonstrated that voluntary trunk control training coupled to visuospatial exploration training while sitting may result in beneficial effects on sitting and standing balance in patients with initially poor trunk control due to stroke, beyond the effects attributable to spontaneous recovery and conventional training.

Stepping responses The use of relatively small force platforms may be the reason for another neglected aspect of standing balance recovery from stroke, which is the ability to make fast and multidirectional stepping responses to unexpected perturbations. In the case of a gross disturbance of the body's vertical orientation, and in the absence of external support to the trunk or the arms, the posture-control system may no longer be able to rely on equilibrium reactions to keep the centre of mass well within the limits of the actual base of support. Instead, it may need to execute a stepping response to adjust the base of support to the movement of the centre of mass to prevent a fall[130]. Under normal circumstances healthy subjects often prefer automatic stepping responses to fixed-support strategies when they are perturbed in various directions, even if maintaining a fixed base of support would theoretically be possible[130-132], perhaps because stepping requires relatively little muscle force. It is possible that stepping responses are even more vital to persons who suffer from impaired equilibrium reactions and muscle force, such as patients with a stroke. It has been reported in patients with chronic stroke that the initiation of paretic hip muscles while taking a voluntary step is relatively preserved compared to the same muscle activity during automatic equilibrium reactions[81]. It might be that the ability to train multidirectional stepping responses is greater than the possibility to influence the efficacy of basic equilibrium reactions following stroke. This hypothesis needs to be corroborated by empirical studies.

Influence of stroke location Whether balance recovery from stroke is influenced by the location of the brain lesion is an important question, but has not been studied extensively. Laufer et al.[22] found that patients with a right-hemisphere stroke of the anterior brain circulation had 37% chance of reaching independent standing after 2 months versus 60% chance for patients with comparable left-hemisphere lesions. However, such an effect of lesion side was not found by Sackley[31]. From the moment patients have reached independent standing, no consistent differences in the recovery characteristics of right- versus left-hemisphere lesions have been reported[22,41,78], although Sackley[31] reported more improvement of lateral postural stability in patients with left-hemisphere (30%) compared to right-hemisphere (7%) lesions. Ustinova et al.[89] found that right-hemisphere patients had somewhat more problems during the initial learning of a voluntary weight-shifting task using visual COP feedback. Many cross-sectional studies have also indicated relatively severe balance problems in patients with right- compared to left-hemisphere lesions, particularly related to visuospatial cognitive deficits[27,88,103,106,124,125,133,134]. However, others reported less marked or no effects of lesion side[6,36,40,93] or even better static and dynamic balance in the case of right-hemisphere lesions[77]. Perhaps more important than the side of stroke is the specific site of the brain lesion. The few studies that have investigated this aspect in patients with unilateral supratentorial stroke indicated that involvement particularly of the parieto-temporal junction is associated with poor static and dynamic balance[89,93,103] and more specifically lesions of the parieto-insular vestibular cortex[93,106]. This association suggests that sensory integration deficits or disturbances of spatial cognition play a major role in the causation of severe standing balance problems after stroke.

Clinical implications Based on the available evidence, no firm conclusions can be drawn about the best therapeutic approach to influence the speed or extent of standing balance recovery in the post-acute phase of stroke. There is little evidence of the efficacy of 'static' or 'dynamic' force-feedback training on either weight-bearing symmetry or postural stability during unperturbed stance. There is preliminary evidence of the efficacy of repetitive sit-to-stand training using biofeedback on dynamic standing balance skills, especially sit-to-stand transfers[91]. The possible efficacy of lower-limb strength training on making sit-to-stand transfers needs further support[92]. In addition, targeted balance training during visual deprivation may be more effective to improve stance stability under complex sensory conditions than the same training with full vision[97]. Similarly, it may be that balance training under dual-task and complex sensory conditions may help to regain sufficient automaticity and flexibility of the various balance skills required in daily life; however, this notion needs to be corroborated by empirical evidence. When balance recovery attenuates, mechanical aids such as canes may improve both weight-bearing characteristics and postural stability during unperturbed standing[51-53], although their influence on dynamic balance skills and gait may be quite different. Hence, with regard to the many possible therapeutic options, the literature is still far from extensive or conclusive. It is expected that this review will help researchers interested in the rehabilitation of patients with stroke to select challenging new study objectives.

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3

Recovery of Standing Balance in Postacute Stroke Patients: A Rehabilitation Cohort Study

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Mirjam de Haart, MD, Alexander C.H. Geurts, MD, PhD, Steven C. Huidekoper, PT, Luciano Fasotti, PhD, Jacques van Limbeek, MD, PhD

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ABSTRACT

Objective: To identify and interrelate static and dynamic characteristics of the restoration of quiet standing balance in a representative sample of stroke survivors in the Netherlands during their inpatient rehabilitation.

Design: Exploratory study using an inception cohort with findings related to reference values from healthy elderly persons.

Setting: Rehabilitation center.

Participants: Thirty-seven inpatients (mean age, 61.6y; mean time poststroke, 10.0wk) with a first hemispheric intracerebral infarction or hematoma who were admitted to retrain standing balance and walking.

Intervention: Individualized therapy.

Main Outcome Measures: Center of pressure fluctuations were registered under each foot and in the sagittal and frontal planes separately by using a dual-plate force platform. The first balance measurements took place as soon as patients were able to stand unassisted for at least 30 seconds as well as 2, 4, 8, and, 12 weeks later. Quiet standing was assessed under 4 conditions: with and without a visual midline reference, with the eyes closed, and while performing a concurrent arithmetic task.

Results: The stroke patients showed excessive postural sway and instability, particularly in the frontal plane, compared with reference values. Frontal plane balance was, however, also most responsive to the effects of balance training and recovery (*P*<.001). The degree of visual dependency for frontal plane balance control showed a significant reduction in time (*P*<.02). Weight-bearing asymmetry, which was most pronounced in patients with disturbed sensibility or ankle clonus, diminished considerably during the first 4 weeks of the follow-up period (*P*<.02). Yet, a substantial degree of weight-bearing asymmetry persisted during the 8 weeks thereafter, and it continued to be aggravated by attentional distraction (*P*<.001). During the same period, static asymmetry (ie, the degree of pes equinovarus loading at the paretic side) and dynamic asymmetry (ie, the extent to which compensatory ankle moments are applied at the nonparetic side) did not show normalization at all, although motor selectivity of the paretic leg improved by 1 stage on the 6-stage Brunnstrom scale (*P*<.001) and the independency level of balance and walking skills improved by 2 points on the 6-point Functional Ambulation Categories (*P*<.001).

Conclusions: Balance recovery in postacute stroke inpatients is characterized by a reduction in postural sway and instability as well as by a reduction in visual dependency, particularly with regard to frontal plane balance. These restoration characteristics may be important factors underlying the relearning of independent standing and walking abilities. The clear lack of normalization for measures reflecting static and dynamic

aspects of postural asymmetry suggests that the functional improvements in balance and gait must be more related to other mechanisms than to the restoration of support functions and equilibrium reactions of the paretic leg.

INTRODUCTION

Impaired postural control is a key characteristic of the mobility problems in stroke patients and is caused by a complex interplay of motor, sensory, and cognitive impairments. Previous studies in stroke patients have identified reduced loading on the paretic lower limb[1-6] and increased postural sway during quiet standing[1,3-5,7] as well as delayed and disrupted equilibrium reactions and impaired anticipatory postural adjustments to body perturbations, especially in the affected leg[8-11]. Together with a general slowness of information processing, this combination of postural deficits causes slow and inflexible motor behavior during various activities of daily life[12-14].

Most of our knowledge of postural control after stroke is based on studies designed to unravel specific aspects of muscular coordination or kinetic and kinematic regulation of standing balance. The studies typically have relatively small cohorts of patients whose motor status in the chronic phase of their stroke is rather good[15,16]. Only a few studies[1,2,4] have dealt with recovery characteristics, although most were limited to assessments made before and after a specific intervention. As a consequence, little information is available about balance recovery over a longer, relatively early period poststroke, that is, during the rehabilitation phase.

The present study focused on the balance recovery of rehabilitation inpatients for 2 reasons: (1) stroke patients who need care in a rehabilitation center are especially likely to have balance problems that interfere with functional independence, while also having some recovery potential, and (2) the repeated assessments required in a longitudinal cohort study to ensure a minimum of drop-outs or missing data are usually best attainable with inpatients. Given this restriction, we made our inclusion criteria as unrestricted as possible to obtain a representative sample of all rehabilitation inpatients with stroke in the Netherlands.

We used force platform registrations primarily because kinetic data represent the efficacy of the equilibrium reactions in both the sagittal and frontal planes, thus providing an overall view of the postural control system[3,17-19]. Posturography is sensitive to the consequences of many different pathologies[17,20-25] as well as to (subtle) changes of the environmental context of the balance task[24-28]. It is also reasonably reliable, has predictive validity with regard to daily life balance performance[18,23,29] and is responsive to functional improvement in various groups of patients[20,23,24,29]. Posturography also is patient friendly and permits easy interpretation of lateralized phenomena. Particularly in the case of a "spastic hemiparesis", lateralized impairments may occur. These impairments include reduced ability to load the paretic leg, impaired use of the affected leg muscles for well-coordinated equilibrium reactions, and (because of muscular imbalance at the ankle) a tendency to overload the affected forefoot (pes equinus) and lateral foot edge (pes varus). Because pes equinovarus may lead to a pathologic heel rise, seen when the patient is standing barefoot, there may even be loss of support base on the affected side, which will further reduce the efficacy of already impaired equilibrium reactions generated through the affected leg. Particularly in the sagittal plane, the force moments generated about the ankle joints through the activity of the lower-leg muscles during quiet standing depend on a firm base of support, and thereby actively influence foot pressure distribution. Because such stabilizing ankle moments are continuously generated, the fluctuations of the foot center of pressure (COP) are greater than the fluctuations of the body center of gravity, especially in the sagittal plane during normal 2-legged standing. The force moments reflect both postural sway and regulatory activity in terms of stabilizing ankle mechanisms[18,30]. Dual-plate posturography permits both static (ie, related to COP position) and dynamic (ie, related to COP movement) characteristics of standing balance to be evaluated for both feet together and for each foot separately.

Because balance problems may easily be masked under relatively simple task conditions (eg, quiet standing with eyes open), we used sensory and cognitive task manipulations in the assessment of patients' balance behavior. This approach reveals control problems, such as (changes in) visual or attentional dependency, that might otherwise remain unnoticed. Visual task manipulations and dual tasks have been used in many studies[7,20,24,28,31-36], after they were first advocated in clinical assessment more than 10 years ago[37,38]. They may disclose "hidden" aspects of motor control and recovery essential to the development of more automated and flexible behavior during complex daily life activities[12,14].

We hypothesized that postural instability and weight-bearing asymmetry would decrease over time and that the decrease would be associated with a decrease in visual dependency and in dual-task interference. We also added a visual vertical midline reference to a texture-rich visual surround. We hypothesized that patients with somatosensory disturbances or hemineglect might especially benefit from this external visual reference, particularly in their weight-bearing symmetry and frontal plane postural stability. Yet, the focus of the study was primarily exploratory: to identify and interrelate the most important posturographic characteristics of the restoration of standing balance in a representative sample of stroke survivors in the Netherlands during their inpatient rehabilitation. Our ultimate goal was to obtain better insight into the underlying mechanisms of functional recovery, irrespective of whether that recovery was spontaneous or induced by training.

METHODS

Participants All patients with a first hemispheric intracerebral infarction or hematoma admitted to our rehabilitation clinic from November 1998 until November 2000 for retraining motor skills and self-care abilities were eligible. Patients who on admission already walked safely and patients with medication or nonstroke-related sensory or motor impairments that could interfere with their postural regulation were excluded. Basing our decisions on practical assessment, we also excluded patients with concomitant cognitive or psychiatric problems that impaired their ability to follow simple verbal instructions. These selection criteria permitted a wide variety of rehabilitation inpatients to participate. Thirty-nine stroke patients were included, 2 of whom were lost to follow-up. One patient suffered from severe secondary seizures, and another patient had to be discharged prematurely because of insurance problems. Thus, an inception cohort of 37 patients was formed.

Table 1: Characteristics of participants (N=37)

Age (y)	61.6±12.9 (27–82)
Time poststroke (wk)	10.0±5.4 (3.3–24.1)
Gender (men/women)	20/17
Type of stroke (infarction/hematoma)	30/7
Hemisphere of stroke (left/right)	13/24

NOTE. Values are mean ± standard deviation (range) or N.

At a minimum, all patients received 5 weekly 30-minute sessions of individual physiotherapy and 3 weekly 30-minute sessions of occupational therapy. These individual therapies were augmented by small-group therapy for improving gross motor skills. The group therapy occupied at least 60 minutes of each working day. This motor rehabilitation was embedded in a more extensive, individualized neurodevelopmental treatment (NDT) rehabilitation program. The NDT program had a general emphasis on optimal use of the paretic body side. Age, stroke type (infarction or hematoma), location (left or right hemisphere), and time poststroke at study entry were registered as potentially relevant biologic characteristics. These data were obtained from the neurologic records, including computed tomography or magnetic resonance imaging scanning. As a reference for our stroke patients, we used posturographic data obtained from a study[32] of healthy elderly subjects (N=23; age, 63.9±9.3y) that underwent the same procedure as applied in the present study. All participants gave informed consent after receiving both verbal and written information about the study and its potential risks. Approval was obtained from the institutional ethics committee.

Equipment Balance registrations were made by means of a force platform consisting of 2 separate aluminum plates, each placed on 3 force transducers[a] (hysteresis and nonlinearity, <1%) that recorded the vertical ground reaction forces[18]. Signals were processed by 6 direct-current amplifiers[b] (nonlinearity, <0.1%) and first-order low-band pass filters with a cutoff frequency of 30Hz. Data were stored after a 12-bit analog-to-digital conversion at a sampling rate of 60Hz. By means of digital moment-of-force calculations, we determined the point of application of the resultant of the ground reactions in a 2-dimensional transverse plane. The calculations were done for each sample, with a maximum error of ±1mm in the lateral and anteroposterior (AP) directions. The coordinates of this COP were passed through a digital, low-band pass, 6-Hz Fourier filter to eliminate high-frequency components arising from noise.

Two parallel support bars were placed beside the force platform and a 300x260-cm screen with alternating black and white 8-cm wide horizontal bars was situated about 2m in front of the platform. This screen covered most of the visual field. This visual surround ensured optimal optic flow for AP postural regulation. In 1 condition, a vertical black bar (width, 8cm) was added to the middle of this visual surround to provide the patients with a left-right reference. During the eyes closed condition, patients wore a pair of closed dark goggles. An integrated 16-bit sound card and 2 external speakers were used to present patients with arithmetic problems during the dual task.

Procedure Five posturographic assessments were made over a period of 12 weeks. The first assessment took place as soon as a patient was able to stand without assistance for 30 seconds or more, that is, grade 4 according to the standing balance scale described by Bohannon[39]. The same assessments were repeated 2, 4, 8, and 12 weeks later. The timing of each patient's first assessment was indicated by the capability of prolonged active knee and hip extension at the paretic body side, sufficiently strong to prevent limb collapse and abnormal trunk flexion during stance. From this moment, standing balance training could commence without external support (ie, "start" of balance training).

Table 2: Functional characteristics of participants (N=37) at the start of balance training and 12 weeks later

	Start of Training	12 Weeks Later
Leg motor selectivity (Brunnstrom)	IV (II–VI)	V (III–VI)
FAC	2 (1-4)	4 (1-5)

NOTE. Values are median scores (range).

The first and last posturographic assessments were accompanied by a clinical evaluation consisting of 2 parts: (1) the principal investigator (MdH) evaluated the subjects' balance and walking skills, rating them according to the 6-point (range, 0–5) Functional Ambulation Categories[40,41] (FAC), and (2) independent, qualified members of the rehabilitation team, who were not actively involved in this study, conducted a standardized physical and neuropsychologic examination.

The physical examination provided data for lower-limb motor selectivity, sensibility, reflex activity, and trunk control. The lower-limb motor selectivity score was according to the 6 motor stages defined by Brunnstrom[42,43]: I, flaccid paralysis; II, increased muscle tone without active movement; III, increased muscle tone with active movements mainly in rigid extension synergy; IV, increased muscle tone with alternating gross movements in extension and flexion synergies; V, muscle tone normalization with some degree of selective muscle control (ie, combined active knee extension and foot dorsiflexion against some resistance); and VI, normal muscle tone and control. The lower-limb sensibility score was obtained by testing position sense at the affected ankle joint in 3 different angles of dorsi- and plantarflexion by mirroring with the nonparetic ankle. In this test, the patient was supine, and the paretic leg was slightly lifted by the investigator. A score was recorded as ''disturbed'' if the patient had a mirroring error greater than 1. The lower-limb reflex activity score was obtained by imposing a fast passive dorsiflexion motion at the affected ankle joint with the patient in the same position as in the former test. The patient had "ankle clonus'' if his/her calf muscle contraction was greater than 1 during sustained dorsiflexion. The patient's trunk control score was determined by the sitting balance item of the Trunk Control Test[40]. Control was rated as "disturbed'' if the patient was unable to stay up sitting on the edge of a bed, feet off the ground, for 30 seconds.

The neuropsychologic examination consisted of a letter cancellation test (the Dutch O-search test), the line bisection test from the Behavioural Inattention Test[44], and the first 6 items of the block design subtest of the Wechsler Adult Intelligence Scale[45] (WAIS). The patients were considered to have visuospatial hemineglect when they showed abnormal lateralization in at least 2 of the 3 neuropsychologic tests, that is, at least 10% fewer cancellations on the affected side in the O-search test, fewer than 7 of 9 points in the line bisection test, and more than 1 mistake in the WAIS block design subtest.

Posturography Patients stood barefoot on the force platform with their arms, alongside their trunk, if possible. Their feet were against a fixed foot frame with the medial sides of their heels 8.4cm apart and each foot placed with toes outward at a 9° angle from the sagittal midline. Before the first posturographic assessment, the base of support (BOS) was determined in both the AP (length of support) and lateral (width of support) directions (see Figs 1A, B). Every balance assessment consisted of 2 consecutive test series. Each test series incorporated 4 quiet-standing tasks and 1 weight-shifting task in a fixed sequence; the sequence was repeated in reverse order to control for time effects related to learning or fatigue. Quiet upright standing was recorded for 30 seconds in each of 4 conditions: (1) facing a screen with black and white horizontal bars (eyes open [EO]), (2) while performing a concurrent arithmetic task (dual task [DT]), (3) while looking at the same visual texture with a vertical black bar as a visual midline reference (visual reference [VR]), and (4) while wearing a pair of closed dark goggles (eyes closed [EC]). In all conditions, patients were asked to stand as still and symmetrically as possible. Each task was preceded by a 5-second anticipation period followed by a low-frequency starting tone. A 1-minute rest was given after each balance test, whereas a longer pause was allowed between the 2 test series. For reasons of brevity, the weight-shifting task will be elaborated in a separate article.

The arithmetic task used in the DT condition consisted of a (varying) verbal sequence of 8 single-digit additions (eg, 7+4=11 or 3+5=7) equally timed over the 30-second period. The patients were instructed to indicate verbally the correctness of each summation by good or fault responses (response time, (2s). After practicing, this arithmetic task was first recorded in a sitting position to obtain a reference of its single-task performance. The number of arithmetic errors, either mistakes or omissions, was noted and compared with the number of arithmetic errors made during the standing balance task.

If necessary for safety, posturographic assessments were guided by the treating physiotherapist. In some patients, especially during the early assessments, the physiotherapist assisted in foot placement and heel loading just before the start of registration. Nevertheless, no physical contact from the physiotherapist or from the support bars beside the platform was allowed during any of the registrations.

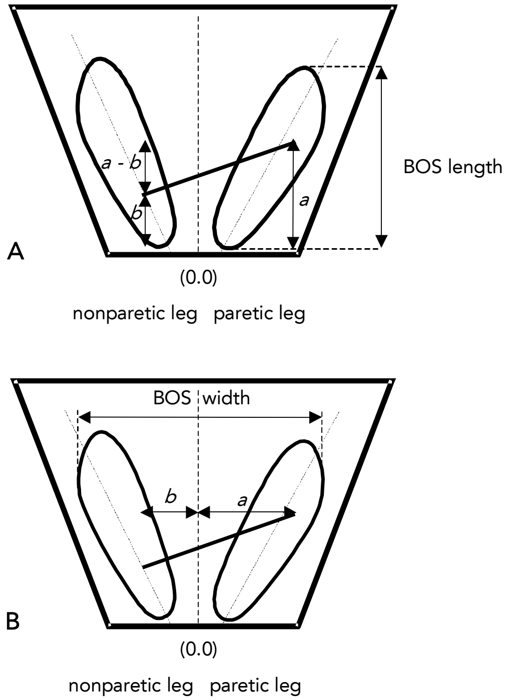

Figure 1. The degree of (A) pes equinus and (B) pes varus as the difference in average COP position between both feet in relation to the length and width of the BOS, respectively. Pes equinus=a – b / BOS length; pes varus= | a – b | / BOS width.

Posturographic Data Analysis *Dynamic parameters.* The root mean square (RMS) of the COP velocities (VCOP) was derived from the balance registrations as the primary measure of postural control or stability in both the frontal and sagittal planes, because it integrates both changes of COP amplitude and shifts in the COP frequency[18]. Further, the RMS amplitude of the COP (ACOP) fluctuations was determined as an estimation of body sway in both planes.

Dynamic asymmetry. The VCOP was determined for each foot separately in both the AP and lateral directions as a measure of the kinetic regulation activity of each leg. To obtain VCOP values congruent with the anatomic orientation of the respective ankle joints, the reference coordinate system was rotated 9° to the left or the right, according to the position of the left and right foot (see Fig. 1). Then, the dynamic asymmetry in regulation activity in each direction was expressed in a quotient as follows:

$$\text{Kinetic regulation asymmetry quotient} = \frac{\text{VCOP}_{\text{nonparetic}}}{\text{VCOP}_{\text{paretic}}}$$

Static parameters. The average position of the COP (PCOP) was expressed as a percentage of the BOS length and the BOS width with the zero-zero point at the rear in the sagittal midline (see Figs 1A, B). Weight-bearing asymmetry was expressed as the lateral PCOP deviation from the sagittal midline toward the nonparetic leg as a percentage of the BOS width. This measure can be regarded as a reasonable approximation of the percentage of body weight overloading on the nonparetic limb. Body inclination was defined as the AP PCOP distance from the posterior plane through both heels as a percentage of the BOS length.

Static asymmetry. To express the degree of forefoot overloading at the affected body side (pes equinus) (see Fig. 1A), the PCOP under the nonparetic leg was subtracted from the PCOP under the paretic leg in the AP direction and related to the BOS length as follows:

$$\text{Pes equinus} = \frac{\text{PCOP}_{\text{AP paretic}} - \text{PCOP}_{\text{AP nonparetic}}}{\text{BOS length}}$$

To express the degree of lateral foot edge overloading (pes varus) (see Fig. 1B) at the paretic body side, the absolute difference between the lateral PCOP under the nonparetic leg and the lateral PCOP under the paretic leg
was related to the BOS width as follows:

$$\text{Pes varus} = \frac{\left|\text{PCOP}_{\text{lateral paretic}} - \text{PCOP}_{\text{lateral nonparetic}}\right|}{\text{BOS width}}$$

Statistical Analysis All posturographic (dependent) parameters were tested in a multivariate analysis of variance[46] (MANOVA) of time (5 follow-up assessments) by condition (EO, DT, VR, EC) with repeated measures on both factors. In second instance, we analyzed the influence of the subjects' biologic and clinical characteristics. Respectively, these were age (<65y vs ≥65y), type and location of stroke, time poststroke (≤8wk vs >8wk) and initial Brunnstrom motor stage (ie, no [≤IV] vs some [>IV] selective muscle control), disturbed sensibility, ankle clonus, disturbed trunk control, and hemineglect. Each characteristic was a between-subjects factor in the MANOVA. Selected differences in functional status (ie, Brunnstrom stage, FAC score) before and after the 12-week follow-up period were analyzed using the Wilcoxon matched-pairs signed-ranks test.

RESULTS

Cohort Five follow-up assessments were completed in 37 stroke patients. Patients' biologic characteristics are in table 1. At the start of the balance training, 24 patients (65%) had a disturbed sensibility in their paretic leg, 19 patients (51%) had an ankle clonus, and 22 patients (59%) had a disturbed trunk control. In 16 patients (43%), some degree of visuospatial hemineglect was found. As for the functional measures, the median Brunnstrom stage was IV (range, II–VI) at the start of the balance training and improved to V (range, III–VI) after 12 weeks ($P<.001$). The median FAC score improved by 2 points from 2 (range, 1–4) at the start to 4 (range, 1–5) at the end of the 12-week period ($P<.001$) (table 2).

Selected static and dynamic parameters of posturography are in tables 3 and 4, respectively. In figure 2A, the group means of the VCOP values in the frontal plane are presented with their 95% confidence intervals (CIs) for the EO and EC conditions for all follow-up assessments together with the reference values obtained from healthy elderly while standing with their eyes opened. Figure 2B represents the same values in the sagittal plane. Clearly, the stroke patients had from 4 to 5 times greater postural instability in both planes compared with the healthy elderly reference values. Averaged over all conditions, the stroke patients showed a mean decrease in VCOP across time of 33% in the frontal plane ($F_{4,33}=12.6$, $P<.001$) and 18% in the sagittal plane ($F_{4,33}=2.9$, $P=.037$). Further analysis revealed that this improvement in postural stability was largely related to a reduction in their ACOP in both planes. A time by condition interaction in the frontal plane ($F_{12,25}=2.93$, $P=.011$) indicated a relatively large improvement for the EC condition. Averaged over time, a main effect of condition occurred in both the frontal ($F_{3,34}=6.9$, $P=.001$) and sagittal($F_{3,34}=10.9$, $P<.001$) planes. This effect was related to approximately 20% greater values of both VCOP and ACOP during visual deprivation. In the sagittal plane, we also found a small but consistent degree of dual-task interference, which was reflected by 14% greater VCOP values. This phenomenon was mainly caused by a higher mean COP frequency. The visual midline reference never had a significant effect on postural stability. In figure 3, the kinetic regulation asymmetry quotient is presented by its group means with 95% CIs for the EO condition for all follow-up assessments in both planes. MANOVA revealed no main or interaction effects of condition or time with regard to this parameter in either plane. Averaged over time, the dynamic asymmetry quotient was approximately 2.1 in the frontal plane and 2.4 in the sagittal plane.

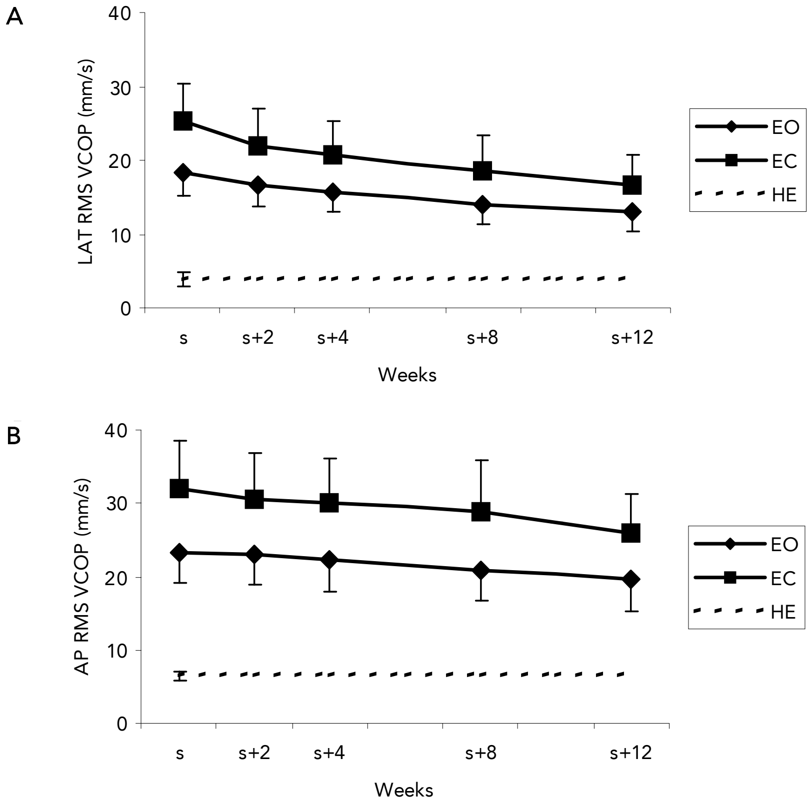

Figure 2. Postural stability, expressed as the RMS of the VCOP in (A) the frontal plane and (B) the sagittal plane for all stroke patients (N=37) during all follow-up assessments. NOTE. 95% CIs are plotted 1-sided for visual clarity. Abbreviations: HE, healthy elderly (N=23); LAT, lateral; S, start of balance training.

Figure 4 shows the group means with their 95% CIs of the degree of weight-bearing asymmetry for the EO and DT conditions for all follow-up assessments. Averaged over all conditions, 13.5% extra weight was born on the nonparetic limb at the start of the balance training. This parameter diminished to approximately 10% during the first 4 weeks after the start of the balance training ($F_{4,33}$=3.9, *P*=.011), but did not diminish further after that time. For comparison, the 95% confidence limits of weight-bearing

Table 3: Average PCOP in lateral and AP directions for all conditions at all follow-up assessments from start of balance training

	PCOP Lateral (% BOS width)					PCOP AP (% BOS length)				
Conditions	S	S+2	S+4	S+8	S+12	S	S+2	S+4	S+8	S+12
EO	12.6 (9.5–15.7)	9.7 (6.4–12.9)	9.5 (6.0–13.1)	8.4 (5.8–11.0)	9.2 (7.1–11.4)	41.8 (40.1–43.5)	42.3 (40.5–44.1)	42.7 (41.1–44.2)	43.4 (41.9–45.0)	43.1 (41.5–44.8)
DT	16.4 (12.9–20.0)	12.9 (9.2–16.7)	11.9 (8.4–15.3)	12.1 (9.3–14.9)	11.2 (8.8–13.7)	41.5 (39.8–43.1)	42.3 (40.7–43.9)	42.4 (40.9–43.9)	42.9 (41.3–44.5)	43.4 (41.8–45.0)
VR	11.9 (8.9–14.8)	10.2 (6.7–13.6)	8.4 (5.2–11.6)	8.3 (5.4–11.1)	8.5 (6.0–11.0)	41.7 (40.1–43.4)	42.9 (41.2–44.6)	42.6 (41.0–44.1)	43.4 (41.9–45.0)	43.4 (41.8–45.1)
EC	13.0 (9.5–16.5)	10.6 (6.9–14.4)	10.7 (7.4–13.9)	9.5 (6.4–12.5)	10.0 (7.1–12.8)	40.7 (38.9–42.5)	40.6 (38.9–42.4)	41.9 (40.4–43.3)	42.2(40.8–43.6)	42.8 (41.2–44.4)

NOTE. Values are mean (95% CI). Abbreviation: S, start of balance training

Table 4: RMS of VCOP in lateral and AP directions for all conditions at all follow-up assessments from start of balance training

	VCOP Lateral (mm/s)					VCOP AP (mm/s)				
Conditions	S	S+2	S+4	S+8	S+12	S	S+2	S+4	S+8	S+12
EO	18.3 (15.2–21.3)	16.6 (13.8–19.5)	15.6 (12.9–18.4)	14.1 (11.3–16.9)	12.9 (10.3–15.6)	23.4 (19.1– 27.6)	23.1 (18.9–27.4)	22.2 (17.9–26.5)	20.9 (16.8–25.0)	19.7 (15.2–24.1)
DT	20.2 (16.9–23.4)	16.7 (13.8–19.6)	17.4 (13.8–21.1)	15.2 (11.9–18.5)	13.9 (10.8–17.1)	25.9 (20.1–31.7)	25.6 (19.8–31.5)	24.8 (19.5–30.1)	23.2 (18.3–28.1)	22.3 (17.1–27.5)
VR	19.3 (15.9–22.8)	15.7 (13.2–18.2)	15.4 (12.2–18.6)	13.7 (10.9–16.5)	12.9 (10.1–15.7)	24.1 (19.1–29.1)	22.2 (18.4–25.9)	21.5 (16.9–26.0)	20.6 (16.2–25.0)	18.9 (15.0–22.9)
EC	25.4 (20.4–30.4)	21.9 (16.8–26.9)	20.7 (16.1–25.3)	18.6 (13.7–23.4)	16.7 (12.6–20.7)	32.1 (25.6–38.6)	30.6 (24.3–36.8)	30.1 (24.2–36.0)	28.8 (21.8–35.9)	26.0 (20.6–31.3)

NOTE. Values are mean (95% CI). Abbreviation: S, start of balance training.

asymmetry in healthy elderly were –3.14 to 0.24. Averaged over time, the dual task resulted in 32% more weight-bearing asymmetry compared with the EO condition ($F_{3,34}$=14.7, *P*<.001). This dual-task interference did not show a clear tendency to diminish during the 12 weeks of follow-up, that is, no interaction effect with time was found. Neither visual deprivation nor adding a visual midline reference had a significant effect on weight-bearing asymmetry. The PCOP in the sagittal plane approximated 41% of the BOS length during all follow-up assessments, which was well within the 95% confidence limits of healthy elderly (39.3%–43.8%).

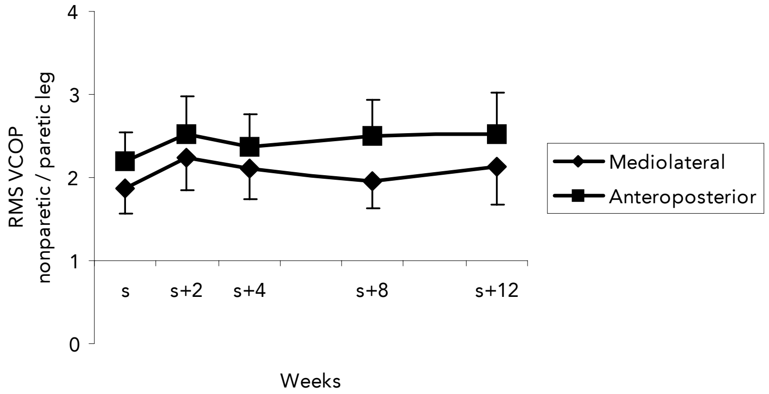

Figure 3. Asymmetry in kinetic regulation activity, expressed as the RMS of the VCOP of the nonparetic leg divided by that of the paretic leg in both the frontal and sagittal planes for all stroke patients (N=37) during all follow-up assessments of the EO condition. NOTE. The 95% CIs are plotted 1-sided for visual clarity.

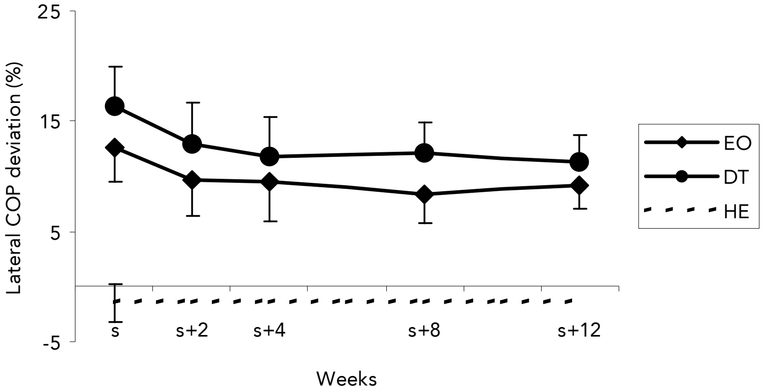

Figure 4. Asymmetry in weight bearing, expressed as the average lateral deviation in COP toward the nonparetic leg with respect to the BOS width, for all stroke patients (N=37) during all follow-up assessments. NOTE. The 95% CIs are plotted 1-sided.

Figure 5 shows the group means with their 95% CIs of the degree of pes equinus and pes varus, respectively. Averaged across time, the degree of pes equinus and pes varus was 7.3% and 1.9%, respectively, while standing with the eyes opened. Pes equinus increased to 7.7% with the eyes closed and to 8.8% during the dual task ($F_{2,35}$=9.1, *P*<.001). Averaged over all conditions, the findings showed some tendency toward a reduction in pes equinus across time, but that tendency did not reach significance.

As for the arithmetic performances, there were no main or interaction effects. In general, the mean number of arithmetic errors was 2.0 while sitting and 1.8 during the dual task (standing).

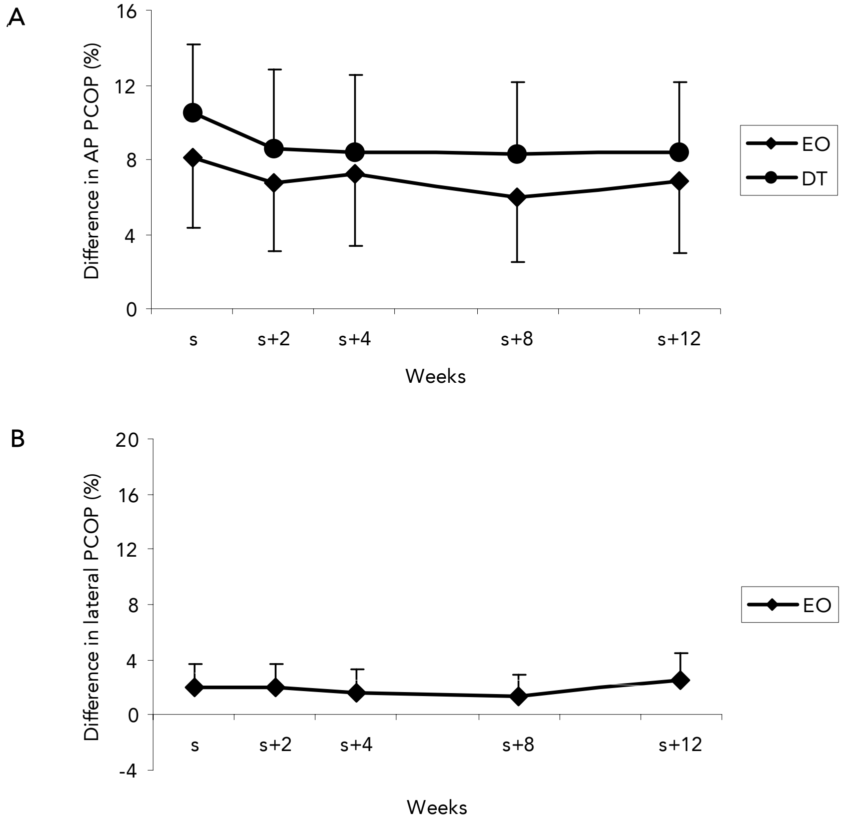

Figure 5. The degree of (A) equinus loading and (B) varus loading on the paretic foot, expressed as the difference in average COP position between the feet with respect to the BOS length and width, respectively, for all stroke patients (N=37) during all follow-up assessments. NOTE. The 95% CIs are plotted 1-sided.

Subgroup Analysis

For the biological characteristics, neither main nor interaction effects were found for age and time poststroke, or for type and location of stroke. As for the influence of the various clinical characteristics at baseline, the initial Brunnstrom scale stage had a main effect on the static asymmetry, which is shown in figure 6 for pes equinus while standing with the eyes opened. The degree of pes equinus was approximately 4 times greater in the 21 patients without selective muscle control (Brunnstrom stages I–IV) than in the 16 patients with at least some degree of selective muscle control (Brunnstrom stages, V–VI) ($F_{1,35}$=6.2, *P*<.02). An interaction effect of condition by motor stage revealed even more pronounced (22% more) forefoot overloading in the subgroup with Brunnstrom stages I through IV during the DT and EC conditions ($F_{3,33}$=6.2, *P*<.002). Only the patients with a Brunnstrom stage V or VI showed a tendency toward symmetrization during their rehabilitation. This tendency, however, did not reach significance. As for pes varus, this static asymmetry could be fully attributed to the subgroup with Brunnstrom stages I through IV ($F_{1,35}$=6.1, *P*<.02).

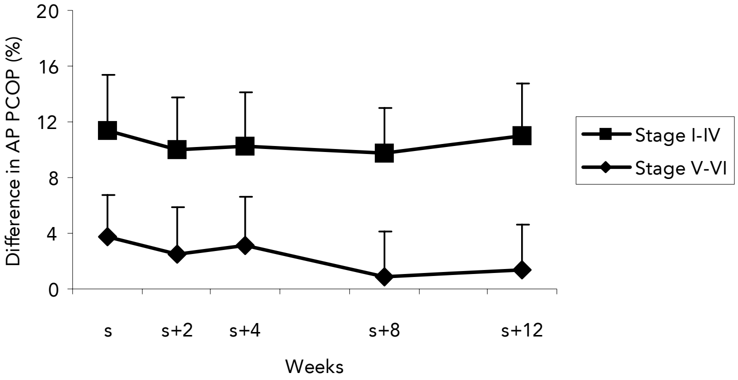

Figure 6. Equinus loading on the paretic foot, expressed as the difference in AP COP position between the feet with respect to the BOS length, for the stroke patients with initial Brunnstrom stage scores of I through IV (N=21) and for those with an initial Brunnstrom stage score V or VI (N=16) during all follow-up assessments of the EO condition. NOTE. The 95% CIs are plotted 1-sided.

The stroke patients presenting with an ankle clonus (N=19) showed on average 98% more weight-bearing asymmetry ($F_{1,35}$=8.0, *P*<.008) and 132% more pes equinus than the patients without ankle clonus (N=18); however, the latter effect was only marginally significant ($F_{1,35}$=2.9, *P*<.10). Also, the stroke patients with disturbed sensibility (N=24) showed 66% more weight-bearing asymmetry than those with normal sensibility (N=13); this effect tended toward significance ($F_{1,35}$=3.7, *P*<.062). No other main or interaction effects were found for the clinical characteristics.

DISCUSSION

The primary goal of this study was to identify and interrelate both static (ie, related to COP position) and dynamic (ie, related to COP movement) characteristics of the restoration of standing balance in a representative group of first-ever stroke survivors during their inpatient rehabilitation in the Netherlands to better understand underlying mechanisms of functional recovery. Only 2 patients were coincidentally lost to follow-up.

As expected, the study sample was relatively young and included comparable numbers of men and women, with, on average, 81% cerebral infarction and 19% cerebral hematoma. As for the location of stroke, right hemisphere lesions were somewhat overrepresented (65%), which may account for a relatively high frequency (43%) of visuospatial hemineglect. The participants had rather severe sensorimotor deficits, as reflected in 59% disturbances of trunk control. As a result, 46% of the participants had a FAC score as low as 1 at study entry. The median 2-point improvement in FAC scores indicated that, for the group as a whole, balance and walking skills developed from "dependent on 1 person" to "fully independent on level ground" during the 12-week follow-up period. For an optimal validity of the posturographic registrations, it was necessary to apply a functional criterion, that is, at least 30 seconds standing without assistance or support, to start the balance registrations for each patient. This functional criterion and the severity of the sensorimotor deficits resulted in an average time poststroke of 10 weeks before independent standing balance registrations could be made. This result is probably characteristic of the situation in the Netherlands, because less severe stroke patients are often rehabilitated on an outpatient basis. Nevertheless, the range of time poststroke varied widely, from 3 to 24 weeks.

Dynamic Characteristics In accordance with previous reports of selected stroke patients[1,3,5,7] and compared with healthy elderly[32], the inpatient rehabilitation cohort in the present study exhibited severe postural instability in either plane, that is, in both sway amplitude (ACOP) and sway control (VCOP). Compared with other rehabilitation patient groups (eg, patients with a lower-limb amputation[24], hereditary neuropathy[25], traumatic brain injury[21], or rheumatoid arthritis[22]) who have been assessed with the same posturographic technique and procedure, the present study's stroke patients had disproportionally severe postural instability in the frontal plane, despite a considerable BOS width. On the other hand, frontal plane balance was most responsive to the effects of balance training and recovery. Although the patients became more stable in both planes, frontal plane balance showed a reduction in VCOP of 33% over the

12-week rehabilitation period versus 18% for sagittal plane balance. This improvement in postural control coincided with a reduction in ACOP. This finding is suggestive of a true posture stabilizing effect.

The stroke patients in the present study showed a clear destabilization with visual deprivation in both planes. This finding could be expected, because 65% of the patients suffered from impaired sensory information from the paretic lower limb. As a nonspecific compensatory strategy observed in many different patient groups, the postural control system tends to rely more on visual information in instances of somatosensory impairments[24,25,47]. By increasing the sway amplitude in the absence of vision, other sensory systems (particularly the vestibulum) may be able to compensate for this visual dependency[48]. Interestingly, the degree of visual dependency in our stroke patients decreased during their rehabilitation at least for frontal plane balance, as indicated by a significant time by condition interaction. At the least, this result seems to indicate some improvement in the somatosensory integration through which proprioceptive and exteroceptive signals from the paretic lower limb are gradually more used in the control of standing balance[48].

The effect of a concurrent arithmetic task on postural control was only significant for sagittal plane balance. The VCOP values were consistently somewhat greater in this direction during the DT condition compared with the EO condition, which was related to a shift in the COP frequency. Apparently, the patients "stiffened up" to some degree in the sagittal plane during the dual task, perhaps as a result of an increased alertness. This effect cannot be readily explained in terms of a true cognitive or dual-task interference, especially because no such effect was present in the frontal plane in which direction the greatest imbalance was observed.

Use of dual-plate posturography allows comparison between the relative contribution of each leg and postural control in terms of its kinetic regulation activity. The more that stabilizing ankle moments are asymmetrically exerted by the lower-leg muscles of a particular leg, the more asymmetry will be found in the kinetic regulation activity between both legs. Such dynamic asymmetry has already been reported for patients with 1-sided lower-limb amputation, who completely lack active control of the artificial ankle and foot. These patients have asymmetry quotients of 3.5 to 4.8 in the sagittal plane and 1.4 to 2.1 in the frontal plane[24]. The stroke patients in the present study showed mean dynamic asymmetry quotients of 2.4 in the sagittal plane and 2.1 in the frontal plane. Compared with patients with lower-limb amputation, the lower values in stroke patients suggest at least some preservation of active control of the paretic ankle and foot, and that this control contributes to standing balance. A comparison of these 2 lateralized disorders of peripheral (amputation) and central (stroke) origin further underscores that frontal plane balance is a particularly important problem in stroke patients, because their dynamic asymmetry quotients are relatively high in this plane. The absence of any condition effect indicates that the degree of dynamic asymmetry reflects a robust efferent compensatory mechanism. The fact that no reduction in dynamic asymmetry across time was found strongly suggests that, on average, the paretic leg's contribution to the generation of posture stabilizing ankle moments did not become normal between the first and last balance assessments, despite its motor selectivity improving at least 1 stage on the Brunnstrom scale in 19 (51%) of the patients.

Static Characteristics In accordance with many other studies[1-6], the present study found a substantial amount of weight-bearing asymmetry, especially in patients who had a persistent ankle clonus or impaired sensibility in their paretic leg. Although weight-bearing asymmetry significantly improved during the first weeks of balance training, there was no improvement thereafter. In other words, about 10% weight-bearing asymmetry persisted in our study cohort. This percentage was clearly outside the 95% CI of healthy elderly. Furthermore, when participants performed a concurrent arithmetic task, weight-bearing asymmetry consistently increased by one third without a clear trend toward diminution of this dual-task interference. This combination of results suggests that, although rehabilitation inpatients with stroke may learn to consciously rely on the support functions of their paretic leg, their weight bearing may never become fully automated. In the case of attentional distraction, patients may still tend to rely more on their nonparetic leg, thus discarding the information from and the potential use of their paretic leg. This lack of frontal balance automaticity may be an important cause of falls in the chronic stroke population[4,49].

If anything, we expected to see the influence of providing a visual midline reference on the degree of weight-bearing asymmetry. Although a minor symmetrization effect on weight-bearing asymmetry existed in the VR condition, this effect was not significant.

The overall COP position in the sagittal plane at first appeared to be noninformative with respect to the postural consequences of stroke and their functional restoration. However, analyzing the PCOP values in the sagittal plane under each foot separately, we found a clear anteroposition of the PCOP under the paretic foot that coincided with a retroposition of the PCOP under the nonparetic foot. Although the anteroposition represents the overloading of the paretic forefoot because of muscular imbalance between the dorsal and ventral lower-leg muscles (pes equinus), the retroposition at the nonparetic side is most likely a compensation to maintain the overall PCOP within normal confidence limits. The degree of pes equinus was slightly but significantly higher in the more complex conditions, in particular during the dual task. Like overall weight bearing, adequate heel loading on the paretic side may remain dependent on conscious control in the more severe stroke patients. Both the degree of pes equinus and its reaction to task complexity were much more pronounced in the patients who did not have selective leg muscle control (Brunnstrom stages I–IV) or in those with ankle clonus than in the patients with at least some degree of muscle selectivity (Brunnstrom stages V–VI) and in those without ankle clonus. Patients with Brunnstrom score of V or VI showed only 4% pes equinus. Although the stroke patients as a group did not demonstrate a significant trend toward normalization of their forefoot overloading, the latter subgroup showed no more than 2% pes equinus at the end of the follow-up period (see Fig. 6). Overloading of the lateral foot edge (pes varus) as a result of muscular imbalance between the inverting and everting muscles at the ankle was only present in the patients with Brunnstrom stages I through IV.

Limitations The results of this study only represent standing balance recovery in a relatively severely affected subpopulation of patients with a first-ever hemispheric stroke who are typical of the stroke patients commonly selected for inpatient rehabilitation in the Netherlands. The individually applied functional criterion for the start of the posturographic assessments precluded early registrations (ie, before independent standing balance had been acquired) in several cases. The application of this functional criterion may also have neutralized the possible influence of various biologic (eg, time poststroke) and clinical (eg, visuospatial hemineglect) characteristics on the posturographic results. Compared with healthy elderly, the included stroke patients showed a high degree of interindividual variability on most of the selected posturographic parameters. There may have been a lack of statistical power, particulary in certain subgroup analyses, because of the still limited number of subjects included in the study.

CONCLUSIONS

To our knowledge, this is the largest study aimed at the recovery of postural characteristics of first-ever stroke survivors during their inpatient rehabilitation. Our results indicate that these patients suffer from severe postural instability as well as from several (both static and dynamic) aspects of postural asymmetry during quiet standing in the frontal and sagittal planes. Functional improvements during rehabilitation appear to be most prominent in the frontal plane, as indicated by a reduction in body sway, in visual dependency, and in weight-bearing asymmetry. These restoration characteristics may be essential to the reacquisition of independent standing and walking abilities as reflected by improved FAC scores. Yet, even after 12 weeks of balance training, a substantial degree of postural instability and asymmetry persisted, the latter still showing susceptibility to attentional distraction. The clear lack of normalization of various parameters reflecting postural asymmetry, including the pattern of foot loading and the use of stabilizing ankle moments at the paretic body side, suggests that improved balance and gait must, at least partly, be related to mechanisms other than the restoration of support functions and equilibrium reactions of the paretic leg.

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SUPPLIERS

[a] Load cells, type LM-100KA, Kyowa Electronic Instruments Company, Limited, Chofu-Higashiguchi Building 2F, 45-6, Fuda 1-chome, Chofu, Tokyo 182, Japan.

[b] RMP DC-amplifier, type MBP 6218, Elan Schaltelemente GmbH, Holzheimer Weg 50, D-4040 Neuss 1, Germany.

4

Restoration of Weight-Shifting Capacity in Patients with Postactue Stroke: A Rehabilitation Cohort Study

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Mirjam de Haart, MD, Alexander C.H. Geurts, MD, PhD, Mylène C. Dault, PhD, Bart Nienhuis Med Eng, Jacques Duysens, MD, PhD

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ABSTRACT

Objectives: To identify and interrelate recovery characteristics of voluntary weight shifting after stroke and to examine whether the assessment of weight shifting adds information about balance recovery compared with the assessment of quiet standing.

Design: Exploratory study using an inception cohort with findings related to reference values from healthy elderly persons.

Setting: Dutch rehabilitation center.

Participants: Thirty-six inpatients (mean age, 61.8 y; mean time poststroke, 10 wk) with a first hemispheric intracerebral infarction or hematoma who were admitted to retrain standing balance and walking.

Intervention: Individualized therapy.

Main Outcome Measures: Center of pressure (COP) displacements were registered during voluntary frontal-plane weight shifting guided by visual COP feedback using a dual-plate force platform. Besides the speed (number of weight shifts) and imprecision (normalized average lateral COP displacement per weight shift), the weight-transfer time asymmetry and the spatiotemporal distribution were determined. Assessments took place as soon as patients could stand unassisted for at least 30 seconds and at 2, 4, 8, and 12 weeks later.

Results: During the 12-week training period, the stroke patients increased both their speed (2.3 hits/30s; 95% confidence interval [CI], 1.1 — 3.4) and precision (37.7 mm/hit; 95% CI, 10.4 — 65.0) of weight shifting. Although the speed appeared to stabilize at a suboptimal level after 8 weeks, precision reached normal reference values after 12 weeks. Both older age (≥ 65 y) and the presence of visuospatial hemineglect negatively affected weight-shifting speed but not its relative improvement in time. During the training period, a small degree of weight-transfer time asymmetry persisted (mean change, .07; 95% CI, -.21 to .36), with an average of 23% slower weight shifts toward the paretic leg, but the spatiotemporal distribution remained symmetrical. The correlations between weight-shifting and quiet-standing control at the end of training were moderate (Spearman ρ range, .50 — .77).

Conclusions: Even subjects with severe stroke who are selected for inpatient rehabilitation are able to improve their speed and precision of weight shifting by reducing the weight-transfer time toward both legs in a proportionate manner. The observed correlations between weight shifting and quiet standing indicate that the assessment of weight-shifting capacity provides unique information about balance recovery after stroke.

INTRODUCTION

Stroke is a major cause of postural imbalance in terms of static (eg, weight distribution[1-6], foot-pressure distribution[1,6]) and dynamic (eg, equilibrium reactions[7,8], weight shifting[2,4,5,9-14]) control. Although stroke patients may suffer from postural instability in all planes[2-3,15], several studies have shown that frontal plane balance is disproportionally affected[6,16]. Because the ability to initiate and control voluntary weight shifts toward either leg is a prerequisite for independent walking, learning to load and unload the affected leg while standing is an important step in the balance and gait training of stroke patients[17]. Hence, making self-generated weight shifts in the frontal plane within the base of support seems an essential ability to train and monitor in these patients[4,5,9,12,14]. Indeed, the potential validity of such dynamic balance tasks with regard to functional balance and gait has been emphasized[18].

Studies have shown that when leaning their body as far as possible in a specific direction without adjusting foot position, stroke patients have difficulties in all planes but mostly in the direction of their paretic leg[2,4,9,11,12]. Also, when shifting from a 2-legged to a 1-legged stance[10,13] or when stepping on stairs of various heights[5], stroke patients show the greatest difficulties with transferring weight toward their paretic leg. On the other hand, loading the nonparetic leg may be troublesome as well[4,5,10-12], which could be due either to subtle neuromuscular impairments ipsilateral to the brain lesion or to a reduced ability to control weight shifts toward the nonparetic side using the leg and hip muscles of the paretic body side. When stroke patients are required to make cyclic bilateral weight shifts in the frontal plane, they clearly make smaller displacements than do healthy elderly people, which has been referred to as a "stabilization" strategy[19]. This stabilization appears somewhat more evident during externally imposed perturbations than when making voluntarily controlled weight shifts, and it coincides with a lack of modulation of the gluteus medius and medial gastrocnemius muscle activity between the paretic and the nonparetic leg[19]. Hence, when assessing weight-shifting capacity after stroke, it seems essential to investigate self-controlled weight displacements toward both the paretic and the nonparetic leg. Such weight shifting should be analyzed not only in terms of overall speed[9,14], sway trajectory[19] or precision[14,18], but also with regard to temporal and spatial asymmetry. As yet, however, no such data are available.

Although there have been studies of dynamic balance training[20-22], none have reported on weight-shifting capacity as an outcome measure. To our knowledge, no observational studies of the recovery of weight-shifting capacity during the rehabilitation of stroke patients have been reported.

Hence, we conducted a cohort study to provide insight into the restoration of voluntary frontal-plane weight-shifting capacity in postacute stroke patients in terms of speed, precision, and spatiotemporal symmetry. It must be emphasized that the aim of our study was not to evaluate any specific treatment but to identify and interrelate recovery characteristics of weight shifting after stroke (whether or not these characteristics are related to 'spontaneous' recovery or to training). To develop effective training strategies, it is important to know what aspects of weight shifting are likely to improve after stroke in terms of speed, precision, and spatiotemporal symmetry and, if so, to what extent compared with healthy elderly persons. A second goal was to assess the relation between weight-shifting and quiet-standing control in the same group of patients, to evaluate the additional information provided by a dynamic balance task compared with static balance tasks.

METHODS

Participants All patients with a first hemispheric intracerebral infarction or haematoma, who were admitted to our rehabilitation clinic for retraining motor skills and self-care abilities during a period of 2 years were eligible. Patients who, on admission, already walked safely and those with medication- or nonstroke-related sensory or motor impairments that could interfere with their postural regulation were excluded. Based on practical assessment, patients with concomitant cognitive or psychiatric problems that impaired their ability to follow simple verbal instructions were also excluded from the study. Thirty-nine stroke patients were included, 2 of whom were lost to follow-up. One patient suffered from severe secondary seizures and another had to be discharged prematurely because of health insurance problems. A third patient had to be omitted from further analysis because of an error in the collection of the weight-shifting data. Thus, an inception cohort of 36 patients was formed.

At a minimum, all patients received 5 weekly 30-minute sessions of individual physiotherapy and 3 weekly 30-minute sessions of occupational therapy. These individual therapies were augmented by small group therapies for improving gross motor skills. These group therapies occupied at least 60 minutes of each working day. This motor rehabilitation was embedded in a more extensive, individualized rehabilitation program with a general emphasis on optimal use of the paretic body side (neuro-developmental treatment oriented). Age, stroke type (infarction or hematoma), location (left or right hemisphere), and time from stroke at study entry were registered as potentially relevant biologic characteristics, based on the neurologic records including computed tomography or magnetic resonance imaging scanning. As a reference for our stroke patients, we used posturographic data obtained from a study[23] of healthy elderly subjects (N=23; mean age, 63.9 ± 9.3 yrs) who underwent the same procedure as applied in our study. All participants gave their informed consent after receiving both verbal and written information about the study and its potential risks. Approval was obtained from the institutional ethics committee.

Table 1: Biological and clinical characteristics of all stroke patients and of the subgroup of patients with at least 5 hits during the weight-shifting task throughout the follow-up period

Characteristics	Stroke patients (N=36)	Subgroup (N=25)
Age (y)	61,8 ± 13,0 (27-82)	59,8 ± 11,9 (34 – 82)
Time post stroke (wk)	10,0 ± 5,5 (3,3-24,1)	10,0 ± 5,7 (3,3 – 24,1)
Sex	19 Male / 17 Female	14 Male / 11 Female
Type of stroke	29 Infarction / 7 Haematoma	22 Infarction / 3 Haematoma
Hemisphere of stroke	13 Left / 23 Right	7 Left / 18 Right
Sensibility	23 disturbed / 13 normal	16 disturbed / 9 normal
Ankle clonus	18 present / 18 absent	14 present / 11 absent
Trunk control	22 disturbed / 14 normal	16 disturbed / 9 normal
Visuospatial hemineglect	15 present / 21 absent	10 present / 15 absent

NOTE. Values are mean ± standard deviation (range) or N.

Equipment Balance registrations were made using a force platform consisting of 2 separate aluminum plates, each placed on 3 force transducers[a] (hysteresis and nonlinearity, < 1%) that recorded the vertical ground reaction forces[24]. Signals were processed by 6 direct-current amplifiers[b] (nonlinearity, < 0,1%) and first-order low-band pass filters with a cutoff frequency of 30 Hz. Data were stored after a 12-bit analog-to-digital conversion, at a sampling rate of 60 Hz. By means of digital moment-of-force calculations, the point of application of the resultant of the ground reaction forces in a 2-dimensional transverse plane was determined. The calculations were done for each sample, with a maximum error of ±1 mm in the lateral and antero-posterior (AP) directions. The coordinates of this centre of pressure (COP) were passed through a digital, low-band pass, 6-Hz Fourier filter to eliminate high-frequency components arising from noise. Two parallel support bars were placed beside the force platform. To provide visual COP feedback, a 15-in (38.1-cm) color monitor was situated slightly below eye level on a height-adjustable table 1m in front of the patient standing on the force platform.

Procedure Five posturographic assessments were made during a period of 12 weeks. The first assessment took place as soon as the patient was able to stand without assistance for 30 seconds or more. The same assessments were repeated 2, 4, 8, and 12 weeks later. The timing of each patient's first assessment was indicated by the capability of prolonged active knee and hip extension at the paretic body side, sufficiently strong to prevent limb collapse and abnormal trunk flexion during stance. From this moment, standing balance training could commence without external support (ie, 'start' of balance training). The first and last posturographic assessments were accompanied by a clinical evaluation consisting of 2 parts: (1) the principal investigator (MdH) evaluated the subjects' balance and walking skills, rating them according to the 6-point (range 0-5) Functional Ambulation Categories[25-26] (FAC) and (2) independent qualified members of the rehabilitation team, who were not actively involved in this study, conducted a standardized physical and neuropsychologic examination.

The physical examination provided data for lower-limb motor selectivity, sensibility, reflex activity, and trunk control. The lower-limb motor selectivity score was based on the 6 motor stages defined by Brunnstrom[27-28] from flaccid paralysis through increased muscle tone and selectivity to normal selective muscle control. The lower-limb sensibility score was obtained by testing position sense at the affected ankle joint in 3 different angles of dorsiflexion and plantarflexion by mirroring the nonparetic ankle. The score was recorded as 'disturbed' if the patient made more than 1 mirroring error. The lower-limb reflex activity score was obtained by imposing a fast passive dorsiflexion motion at the affected ankle joint. The patient had 'ankle clonus' if the number of calf muscle contractions was greater than 1 during sustained dorsiflexion. The patient's trunk control score was determined by the sitting balance item of the trunk control test[26]. Control was rated as 'disturbed' if the patient was unable to sit erect on the edge of a bed, feet off the ground, for 30 seconds.

The neuropsychologic examination consisted of a letter cancellation test (the Dutch O-search test), the line bisection test from the Behavioural Inattention Test[29], and the first 6 items of the block design subtest of the Wechsler Adult Intelligence Scale (WAIS)[30]. The patients were considered to have visuospatial hemineglect if they showed abnormal lateralization in at least 2 of the 3 neuropsychologic tests—that is, at least 10% fewer cancellations on the affected side in the O-search test, fewer than 7 of 9 points in the line bisection test, and more than 1 error in the WAIS block design subtest.

Posturography Patients stood barefoot on the force platform with their arms alongside their trunk, if possible. Their feet were positioned against a fixed foot frame with the medial sides of their heels 8.4cm apart and each foot placed with toes outward at a 9° angle from the sagittal midline. Before the first posturographic assessment, the base of support (BOS) was determined in both the lateral (ie, the distance between the heads of the fifth metatarsal bones of both feet) and the AP (ie, the distance from the rear of the heel to the tip of the great toe) directions while standing on the force platform. In addition, the distance between the anterior borders of the distal tibiae was assessed to obtain a measure of the individual stance width. Every balance assessment consisted of 2 consecutive test series. Each test series incorporated four 30-second quiet-standing tasks (standing with the eyes open, with the eyes closed, with a visual vertical midline reference, and while performing a concurrent arithmetic task) and one 30-second weight-shifting task in a fixed sequence, which was repeated in the reversed order to neutralize any time effects. A 1-minute rest was allowed after each balance test, whereas a longer pause was allowed between the 2 test series. The methods and primary results of the quiet-standing tasks have been described in a companion paper[6]. Selected data from the quiet standing conditions will be presented in this report to examine the association with weight-shifting capacity.

The weight-shifting task required voluntary loading and unloading of both the paretic and nonparetic legs using visual COP feedback. The actual COP position was continuously displayed on the monitor as a black cursor moving on a gray background. A real-time (lag time, ~ .016s), real-size visual feedback was provided, in which up-down and left-right cursor movements corresponded to AP and lateral COP displacements, respectively. In addition, 2 stationary squares were presented at either side of the virtual vertical through the middle of the screen, the latter corresponding to the body's sagittal midline. Each square consisted of 4 blue lines of 30mm long. The lateral position of the centers of the squares was individually determined at 15% of the stance width at each side of the sagittal midline. In this way, weight bearing of approximately 65% on each leg was required to bring the cursor to the middle of the corresponding square. In the AP direction, the centers of the squares were given fixed positions at a distance of 40% of the length of support from the rear, corresponding to the average COP position in the sagittal plane in healthy subjects[23]. The target square in which direction weight had to be transferred was indicated by the color yellow, whereas the non target square was blue. The essence of the required balance task is shown in figure 1.

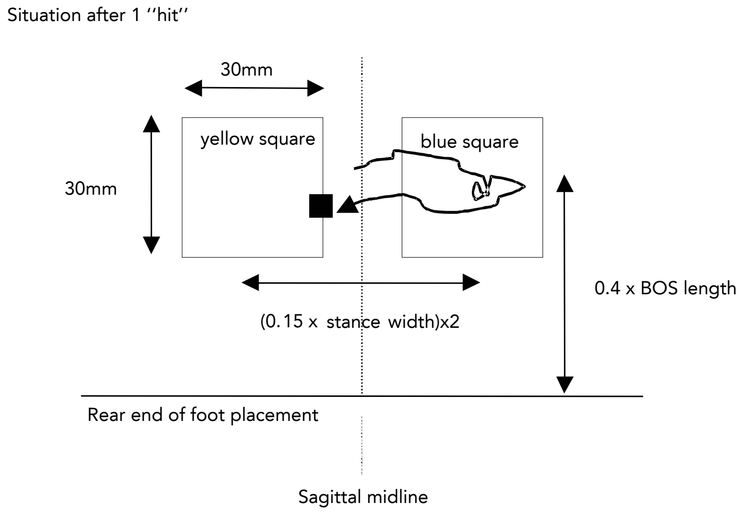

Figure 1. Size and position of the target squares with regard to the BOS length and stance width. The stance width is the distance between the anterior borders of both tibiae.

Subjects were instructed to laterally shift their COP from left to right and vice versa between the 2 squares. They had to maintain their COP for at least 1 second within each target square to make a hit, which was indicated to the subjects by a change in filling color. As soon as a hit was made, the contralateral square became the target and turned into yellow. The start of the weight-shifting registration was preceded by a 5-second anticipation period, which was indicated on the monitor by projecting the numbers 5 to 1. Then, the first target was randomly assigned by the computer. Patients were instructed to start from a comfortable position and to make as many weight shifts as fluently as possible. Because no fixed rhythm was imposed, each subject determined his/her own speed and precision. The weight-shifting task was practiced for several minutes before its first performance, until each subject showed an optimal understanding and individual ability. No physical contact or use of the support bars was allowed during any of the registrations. This weight-shifting task has already proved to discriminate patients with traumatic brain injury or with a lower-limb amputation from healthy controls and to be sensitive to the effects of recovery and training in these groups, in terms of both speed and precision[31-33].

Data analysis The number of target hits (N) in 30 seconds was selected as a measure of the speed of weight shifting. To assess the precision of weight shifting, an imprecision measure (*P*) was used[14]. First, the total COP displacement in the lateral direction (in millimeters) was divided by the number of full weight shifts (N – 1) to obtain the average lateral COP displacement per weight shift. Second, because the target distance was related to the individual stance width, this measure was then normalized to the average stance width of all participants according to the following equation:

$$P = \frac{\left(\frac{\sum_{i=1}^{1799} \left| X_{i+1} - X_i \right|}{N-1} \right) * \overline{R}}{R_{ind}} \qquad (1)$$

where X_i is the lateral COP coordinate, i is the time sample, N is the number of hits, $\overline{R}$ is the average stance width, and R_{ind} is the individual stance width. In addition, the average time needed to transfer weight from the nonparetic to the paretic leg was divided by the average time needed to shift from the paretic to the nonparetic leg to obtain a measure of weight-transfer time asymmetry (A) using the following equation:

$$A = \frac{\bar{t}(nonparetic \rightarrow paretic)}{\bar{t}(paretic \rightarrow nonparetic)} \qquad (2)$$

where $\bar{t}$ is the mean transfer time in a specific direction (ie, the total weight-transfer time divided by the number of full weight shifts in this direction). For the healthy elderly subjects the mean transfer time from the right to the left leg was divided by the mean transfer time from the left to the right leg. Whereas the speed of weight shifting (number of hits) could be determined for all balance registrations, the imprecision and weight-transfer time asymmetry were calculated only for those registrations with at least 2 full weight shifts in either direction (ie, N > 4). For each balance task, the comparable parameters derived from the 2 test series were averaged. However, if just 1 of 2 registrations resulted in more than 4 hits, only this registration was used to calculate the imprecision and time asymmetry. To measure the spatiotemporal distribution of the COP trajectory during weight shifting, the percentages of time spent within

specific areas inside and outside the target area (ie, the area of and in between the 2 targets; see patterned area in Fig. 2) were determined.
As for the quiet-standing tasks, the root mean square (RMS) value of the COP velocity (VCOP) in either the lateral or the AP direction was selected as the primary measure of quiet-standing control, because it integrates changes in both amplitude and frequency of the COP fluctuations (see also de Haart et al.[6]).

Statistical analysis All posturographic (dependent) parameters were tested in a multivariate analysis of variance[34] (MANOVA), with repeated measures on the factor time (5 follow-up assessments). The influence of various biologic and clinical characteristics was analyzed; these were age (< 65 y vs ≥ 65 y), type and location of stroke, time post stroke (≤ 8 wk vs > 8 wk) and initial motor stage (no [Brunnstrom stage ≤ IV] vs some [Brunnstrome stage >IV] selective muscle control), disturbed sensibility, ankle clonus, disturbed trunk control, and visuospatial hemi-neglect. Each characteristic was used as a between-subjects factor in the MANOVA. Selected differences in functional status (ie, Brunnstrom stage, FAC score) before and after the 12-weeks follow-up period were analyzed using the Wilcoxon matched-pairs signed-ranks test. Differences in the time spent within a specific area were analyzed by using either paired or unpaired *t* tests for within- and between-subjects comparisons, respectively. The association between quiet-standing control (VCOP lateral, VCOP AP) and weight-shifting control (speed, imprecision) was assessed by calculating Spearman correlation coefficients.

RESULTS

Cohort Five follow-up assessments were completed in 36 stroke patients, whose main biologic and clinical characteristics are listed in table 1. As for their functional capacity, the median Brunnstrom stage was IV (range, II-VI) at the start of the balance training and improved to V (range, III-VI) after 12 weeks (P<.001). The median FAC score improved by 2 points from 2 (range 1-4) at the start to 4 (range 1-5) at the end of the 12-week period (P<.001). Eleven patients failed to make a minimum of 5 weight shifts in at least 1 of the follow-up assessments; therefore, a reduced sample of 25 patients was used to calculate the changes in imprecision and weight-transfer time asymmetry. This subgroup did not show significant differences in Brunnstrom stage or FAC score at the start or at the end of the balance training compared with the total group of stroke patients. The number of hits, the imprecision measure, and the weight-transfer time asymmetry are presented with their 95% confidence intervals (CIs) in table

2 for all the follow-up assessments, together with the reference values obtained from the healthy elderly.

For the patients with stroke, a mean increase of 2.3 hits/30 seconds (95% CI, 1.1—3.4) in weight-shifting speed across time was found ($F_{4,32}$=5,18, *P*=.002); however, even after 12 weeks, the stroke patients did not reach the same number of hits as did the healthy elderly subjects. Instead, after 8 weeks of training, weight-shifting speed appeared to stabilize. In contrast, the imprecision measure showed a mean decrease of 37.7 mm/hit (95% CI, 10.4—65.0) ($F_{4,21}$=1.78, *P*=.17) and, after 12 weeks, reached the same level of precision as did the healthy elderly subjects.

The weight-transfer time toward either leg was equal in the healthy elderly subjects but not in the stroke patients. Whereas the healthy elderly subjects needed an average of 2.6 seconds to make 1 weight shift, the stroke patients needed an average of 4.3 seconds to make a weight shift to the paretic leg and 3.5 seconds to transfer their weight onto the nonparetic leg during the first assessment. The average weight-transfer time asymmetry measure showed a mean change of .07 (95% CI, -.21 to .36) throughout the follow-up period, except for a marked increase in asymmetry (A=1.6) during the second assessment ($F_{1,24}$=1.80, *P*=.19).

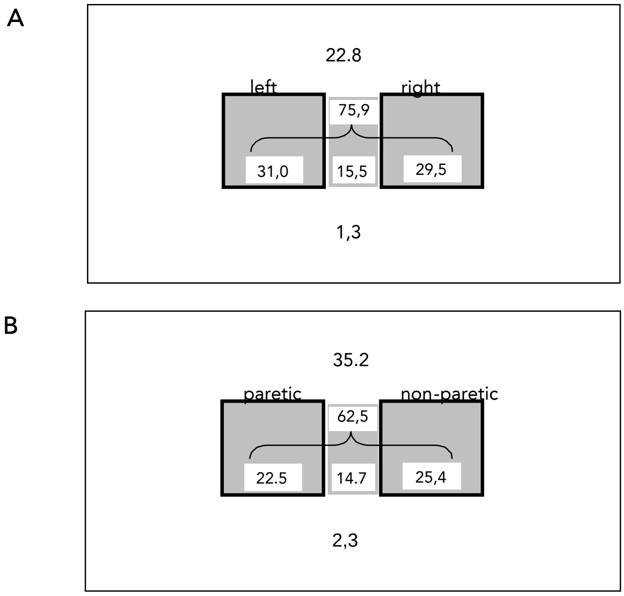

Figure 2. Percentages of time spent inside and outside the target area for (A) healthy elderly subjects (N=23), and for (B) the stroke patients (N=36), averaged over all follow-up assessments (N=5).

In the ideal situation, the COP trajectory would move only within the target area (see patterned area in Fig. 2). Averaged over all assessments, the stroke patients spent less time (62.5%) in the target area than did the healthy elderly subjects (75.9%) (t_{56}= -2.67, *P*=.004). Although the stroke patients improved their time spent within the target area from 58.5% at the start to 64.7% at the end of the training period, this improvement did not reach significance (t_{35}=-1.69, *P*=.10). Of the time spent outside the target area, the healthy elderly subjects and the stroke patients deviated mainly anteriorly (22.8% and 35,2%, respectively). In the group with stroke, for both the time spent within the target area and outside, there were no significant asymmetries in favor of the paretic or the nonparetic leg.

Subgroup analysis For the biologic characteristics, a main effect was found for age on the speed of weight shifting ($F_{1,34}$=14.78, *P*<.001) (Fig. 3). Patients 65 years and older were significantly slower (averaged over time, 6.6 hits) than those younger than 65 years (averaged over time, 9.6 hits). Both groups appeared to stabilize their performance after 8 weeks of balance training. No main effects were found for time from stroke nor for the location or type of stroke.

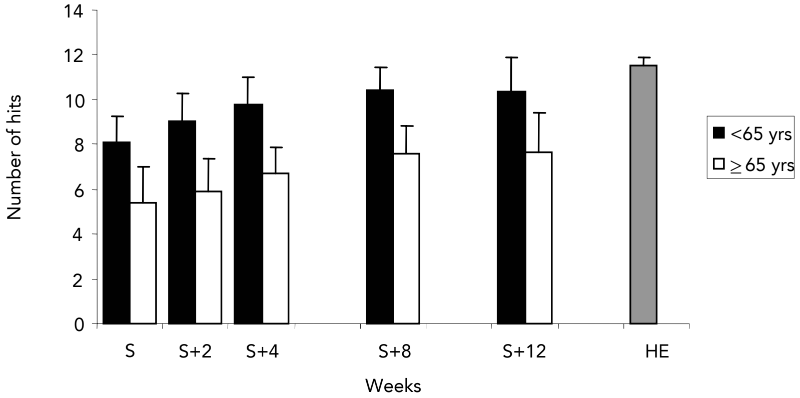

Figure 3. Speed of weight shifting, expressed as the number of hits, for the stroke patients younger than 65 years (N=20) and for those 65 years and older (N=16) at all follow-up assessments. The 95% CIs are plotted 1-sided. Abbreviations: HE, healthy elderly (N=23); S, start of balance training.

As for the influence of the various clinical characteristics at baseline, the presence of visuospatial hemineglect had a negative (20%) effect on the weight-shifting speed ($F_{1,34}$=4.21, *P*<.05), which is illustrated in figure 4. Both patients with and without hemineglect improved their performance across time, but showed stabilization after 8 weeks of balance training. Stroke patients with hemineglect showed a relatively large weight-transfer

Table 2: Speed, precision and symmetry of weight shifting for all follow-up assessments

Time (wk)	S	S+2	S+4	S+8	S+12	HE
Number of hits (N=36)	6.9 (5.8 – 8.0)	7.6 (6.5 – 8.7)	8.4 (7.4 – 9.5)	9.2 (8.3 – 10.1)	9.2 (7.9 – 10.4)	11.5 (10.8 – 12.2)
Imprecision (mm)* (N=25)	154 (124.3 – 183.7)	138 (116.3 – 159.6)	139.7 (104.1 – 175.3)	126.4 (100.0 – 152.8)	116.4 (98.6 – 133.9)	118.8 (103.5 – 134.2)
Time asymmetry† (N=25)	1.3 (1.1 – 1.5)	1.6 (1.1 – 2.0)	1.3 (1.1 – 1.4)	1.2 (1.1 – 1.4)	1.2 (1.0 – 1.4)	1.0 (0.9 – 1.1)

NOTE. Values are means and 95% confidence intervals. Abbreviations: HE, healthy elderly; S, start of balance training. * Imprecision is the normalized average COP displacement per weight shift in the frontal plane. †Time asymmetry is the average time needed for weight transfer to the paretic leg divided by average time needed for weight transfer to the nonparetic leg.

Table 3: Spearman correlations coefficients (ρ) for the relationship between weight-shifting capacity (speed and precision) and quiet-standing control (RMS COP Velocity or VCOP) at the start and at the end of the balance training (N=25)

Parameters		Speed (no. of hits)		Imprecision*	
	Tasks	Start of balance training	End of balance training	Start of balance training	End of balance training
VCOP lateral	EO	-.23	-.70‡	.64‡	.77‡
	EC	-.06	-.59‡	.48‡	.66‡
	DT	-.44‡	-.74‡	.63‡	.72‡
	VR	-.15	-.67‡	.59‡	.75‡
	Average	-.19	-.67‡	.60‡	.72‡
VCOP AP	EO	-.41‡	-.54‡	.78‡	.71‡
	EC	-.31	-.57‡	.66‡	.66‡
	DT	-.51†	-.64‡	.78‡	.74‡
	VR	-.26	-.50‡	.70‡	.64‡
	Average	-.43‡	-.60‡	.82‡	.72‡

Abbreviations: DT, dual task; EC, eyes closed; EO, eyes open; VR, vertical midline reference. * Imprecision is the normalized averaged COP displacement per weight shift in the frontal plane. †significant at p<.01, ‡ significant at p<.05.

time asymmetry (A=1.4). No significant effects were found for initial motor stage, sensibility, reflex activity, or trunk control.

Association with quiet standing The association between weight-shifting and quiet-standing control was examined at the start and at the end of the training period by correlating both weight-shifting speed and imprecision with the RMS COP velocity in the frontal (VCOP lateral) and sagittal (VCOP AP) planes averaged over conditions and during each of the standing conditions alone. Table 3 shows significant and substantial associations of both weight-shifting speed (mainly at the end of the training) and imprecision (at the start and at the end of the training) with VCOP lateral and with VCOP AP during all 4 quiet-standing conditions.

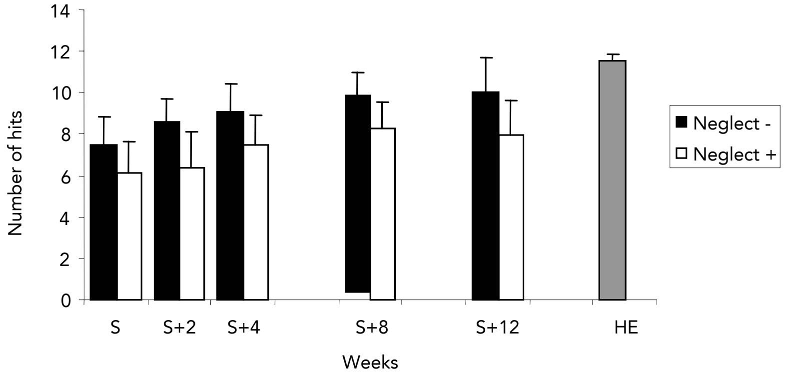

Figure 4. Speed of weight shifting, expressed as the number of hits, for the stroke patients without a visuospatial hemineglect (N=21) and for those with a visuospatial hemineglect (N=15) at all follow-up assessments (healthy elderly, N=23). The 95% CIs are plotted 1-sided.

DISCUSSION

The primary goal of this study was to provide insight into several characteristics of the restoration of weight-shifting control in first-ever postacute hemispheric stroke survivors during 12 weeks of inpatient rehabilitation, irrespective of the causal mechanisms. For this purpose, an instrumented dynamic balance task was used that required patients to make voluntary well-controlled weight shifts in the frontal plane while using real-time and real-size visual COP feedback. This task was analyzed in terms of speed and precision and with regard to spatiotemporal symmetry, to identify a possible resymmetrization process. During the training period, balance and walking skills of the stroke group as a whole developed from 'dependent on one person' to 'fully independent on level ground', whereas leg muscle selectivity improved from 'gross alternating muscle synergies' to 'some degree of selective muscle control'.

Speed and precision The posturographic results showed that, at the start of the training, the selected stroke patients made fewer weight shifts and were less precise than were the healthy elderly subjects, which indicates that both the speed and precision of weight shifting are affected by stroke. During the follow-up period, the stroke patients became significantly faster (33%) and more precise (25%). However, whereas the precision of weight shifting reached normative reference values after 12 weeks, the increase in speed stabilized after 8 weeks without reaching the performance level of the healthy elderly.

Stroke patients 65 years and older were significantly slower than those younger than 65 years at all assessments, yet both age groups showed quite similar recovery profiles. The relatively pronounced slowness in the elderly stroke patients can be understood in view of the fact that the applied balance task requires integration of (artificial) visual feedback with other sources of sensory input to program and execute well-controlled weight shifts under time pressure. Indeed, several studies[14,35-37] have shown aging effects on sensory integration and central processing time related to balance performance. Subgroup analysis also showed a negative effect of visuospatial hemineglect on the speed of weight shifting. Patients with hemineglect showed a relatively large weight-transfer time asymmetry (A=1.4) as well. Because patients with hemineglect suffer from deficits in distributing their attention over both sides of their body and action space[38], they may experience disproportional problems with visually controlled weight shifting, especially to their paretic leg. Neither age nor the presence of visuospatial hemineglect, however, seemed to affect the relative improvement of weight-shifting speed during the rehabilitation. All patient groups gradually improved and tended to stabilize their performance in terms of speed after 8 weeks of training.

Spatiotemporal symmetry On average, the stroke patients needed 23% more time to make a weight shift to their paretic leg than they did when shifting to their nonparetic leg, which remained more or less constant during the training period. On the one hand, this degree of weight-transfer time asymmetry seems rather small, considering the large differences in sensorimotor functions between the paretic and nonparetic legs in most patients. On the other hand, the observed weight-transfer time asymmetry does not tend to diminish. This pattern of results may indicate that stroke patients have difficulties with making weight shifts to both legs, not only the paretic one, which would be in accordance with other studies[4,5,10-12].

This conclusion is supported by analyzing the spatiotemporal distribution of the COP displacements during weight shifting. Both inside and outside the target area, the stroke patients did not show a significant asymmetry with regard to the time spent on their paretic versus nonparetic side, yet, they were generally less efficient than the healthy elderly subjects, both at the start and at the end of the training, because they spent more time outside the target area. When outside the target area, both patients and healthy elderly subjects deviated mainly anteriorly, which probably reflects a safety strategy to avoid posterior falls.

Association with quiet standing Significant correlations were found between the control of quiet standing and the precision of weight shifting among individual patients. Remarkably, weight-shifting precision was as equally associated with sagittal- as with frontal-plane control during quiet standing, yielding shared variances (Spearman $\rho^{2)}$ ranging from 23% to 61% (see table 3). Also, for the speed of weight shifting, there were significant correlations with quiet-standing control in both planes; however, more at the end (ρ^2 range, 25%-55%) than at the start of the training period. On the one hand, these reasonably fair associations between weight shifting and quiet standing seem to imply that the control of both tasks relies, at least partly, on common physiologic mechanisms. On the other hand, the shared variances of the selected parameters are low enough to conclude that the assessment of voluntary weight-shifting capacity significantly adds information about individual balance performance in stroke patients, compared with the assessment of quiet-standing tasks alone. This general conclusion is supported by the results of other studies[18,19]. Our results suggest that this additional information may be particularly relevant in the case of poor balance skills (ie, at the start of a training program).

Limitations The results of our study are representative of weight-shifting restoration only with regard to a specific subgroup of first-ever hemispheric stroke patients, which is commonly selected for inpatient rehabilitation in the Netherlands. From the fact that 61% of the included patients had disturbed trunk control and 44% had a FAC score as low as 1 at study entry, it is evident that the selected patient sample is characterized by relatively severe sensorimotor deficits, which causes dependence in performing most daily activities. Because a functional criterion was applied for the start of the posturographic assessments in individual patients (ie, 30s independent standing), the time from stroke varied considerably at study entry (see table 1). As a result, the possible influence of various other biologic or clinical characteristics that covary with the time from stroke (eg, leg muscle selectivity) may have been neutralized. Although, to our knowledge, this is the first study that investigates the restoration of weight-shifting capacity over a 12-weeks period after stroke, the number of patients included was limited, which may have led to a lack of statistical power, especially in those analyses done on subgroups of patients.

CONCLUSIONS

Even severe stroke patients who are selected for inpatient rehabilitation to retrain gross motor skills can substantially improve their weight-shifting capacity in the frontal plane during a 12-week training period, in terms of both speed and precision. Unlike the speed of weight shifting, precision may even reach the performance level of the healthy elderly. An advanced age (> 65 yrs) and the presence of visuospatial hemi-neglect primarily affect the absolute weight-shifting speed but not its improvement over time. Greater weight-shifting speed is accomplished by a reduction in weight-transfer time to both the paretic and the nonparetic leg in a proportionate manner, which is indicated by a persisting small degree of weight-transfer time asymmetry. In addition, the spatiotemporal distribution of the weight-shifting activity appears remarkably symmetric, although more anterior deviation occurs in stroke patients than in the healthy elderly. In addition to static balance assessments, the assessment of weight-shifting capacity provides unique information about balance recovery after stroke. These observational data may guide the development and evaluation of new rehabilitation strategies to improve weight-shifting capacity and related functional activities in stroke patients.

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SUPPLIERS

[a] Load cells, type LM-100KA, Kyowa Electronic Instruments Company, Limited, Chofu-Higashiguchi Building 2F, 45-6, Fuda 1-chome, Chofu, Tokyo 182, Japan.

[b] RMP DC-amplifier, type MBP 6218, Elan Schaltelemente GmbH, Holzheimer Weg 50, D-4040 Neuss 1, Germany.

5

Selected Posturographic Parameters are Associated with Gait Dependency in Patients with Postacute Stroke

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Re-submitted:
Mirjam de Haart, MD, Anita Beelen, PhD, Jacques Duysens, MD, PhD,
Alexander C.H. Geurts, MD, PhD

ABSTRACT

Objective: To investigate which posturographic parameters are associated with ambulation dependency in patients with postacute supratentorial stroke.

Design: Cohort study.

Setting: Rehabilitation center.

Participants: Thirty-seven inpatients (mean age 61.6 yrs, mean time post-stroke 10.0 weeks) with a first hemispheric intracerebral infarction or hematoma who were admitted to retrain standing balance and walking.

Intervention: Individualized therapy.

Main Outcome Measures: Center of pressure (COP) fluctuations were recorded in the lateral and anteroposterior (AP) directions separately, using a dual-plate force platform while quietly standing with and without a visual vertical midline reference, with the eyes closed, and while performing a concurrent arithmetic task, as well as while making voluntary lateral weight shifts guided by visual COP feedback. Gait dependency was assessed with the Functional Ambulation Categories (FAC). Balance and gait assessments took place as soon as a patient was able to stand unassisted for 30 seconds as well as 2, 4, 8, and 12 weeks later.

Results: Both the dependency level of gait and balance performance improved substantially over the 12 weeks of the study. Lateral postural instability in quiet stance, either with the eyes open, with a visual vertical midline reference or with the eyes closed, was negatively associated with the FAC score, each condition explaining 37% of the variance in the FAC score ($p<.05$). The degree of weight-bearing asymmetry was negatively associated with the FAC as well, explaining 35% of its variance ($p<.005$), however, only during visual deprivation. As for voluntary lateral weight shifting, the speed was associated with the FAC, explaining 32% of its variance ($p<.02$).

Conclusions: Both static and dynamic postural instability in the frontal plane and, to a lesser degree, lateral weight-bearing asymmetry are associated with ambulation dependency in the postacute phase of stroke. These findings suggest that standing balance training, as a prerequisite for independent walking, should specifically focus on these lateral aspects of postural control after supratentorial stroke.

INTRODUCTION

Force-platform posturography has developed into a widely used and accepted method to evaluate and monitor different aspects of standing balance in patients following stroke. Several postural deficits, characteristic of the consequences of supratentorial stroke, have been demonstrated such as reduced and abnormal spontaneous loading on the paretic limb[1-6], impaired postural stability[2-3, 6-7] as well as asymmetry in kinetic regulation activity between both legs[6] during unperturbed standing. Impaired voluntary weight-shifting capacity towards both the paretic and non-paretic leg has been demonstrated by posturography as well[5,8-9]. Although force-platform posturography provides reliable and sensitive kinetic information that reflects postural stability[10-13], it remains essential that these laboratory oriented assessments also reflect functional balance performance. Until now, several posturographic characteristics, in particular parameters related to the velocity of center-of-pressure (COP) movements during quiet standing, have been associated with clinical measures of functional balance in both postacute and chronic stroke (r ranging from -.52 to -.91)[14-17]. As for gait in the chronic phase of stroke, COP displacements have been associated with maximum walking velocity and asymmetry of the stance-phase duration (r ranging from -.68 to -.77)[18]. Furthermore, the walking item of the Motor Assessment Scale has been associated with maximum voluntary weight-shifting capacity in the postacute phase of stroke (r ranging from .77 to .78)[8]. Apparently, force-platform parameters related to both active weight shifting and spontaneous body sway can explain on average 50% of the variance (r^2) of several functional balance and gait measures in patients with stroke[8,14-18,24].

Although independent walking is one of the main goals in the rehabilitation of patients with stroke, a possible relationship between the dependency level of hemiparetic gait and specific posturographic abnormalities has not yet been determined. Indeed, if posturographic parameters would be substantially related to any aspect of gait, one would expect an association with the dependency level of walking, because of its theoretical relationship with dynamic balance. Any meaningful association would be of clinical relevance to identify specific balance training goals for achieving functional independency. Hence, the present study was undertaken to investigate the relationship of selected posturographic force-platform parameters with the dependency level of gait as assessed with the Functional Ambulation Categories (FAC) in patients with supratentorial stroke during their postacute rehabilitation. The 6-point FAC scale (0-5) is the most frequently used assessment tool to categorize patients according to their basic ambulatory skills irrespective of speed, endurance or the use of walking aids (see table 1). Although the FAC scale has already demonstrated good validity and reliablity[25-30], a significant association with posturographic results would further support its validity. Based on earlier findings that particularly frontal-plane balance is sensitive to the consequences of stroke and the subsequent recovery from stroke[6], we hypothesized that particularly posturographic parameters reflecting lateral postural stability would be associated with the FAC.

Table 1: Functional Ambulation Categories

No	Categories	Guidance
0	Nonfunctional (unable)	Patient cannot walk, or requires help of two or more people
1	Dependent (level 2)	Patient requires firm continuous support from one person who helps carrying weight and with balance
2	Dependent (level 1)	Patient needs continuous or intermittent support of one person to help with balance or co-ordination
3	Dependent (supervision)	Patient requires verbal supervision or stand-by help from one person without physical contact
4	Independent (on level ground)	Patient can walk independently on level ground, but requires help on stairs, slopes or uneven surfaces
5	Independent	Patient can walk independently anywhere

Source: Holden et al. 1984[21], Wade 1992[29]

METHODS

Patients All patients with a first supratentorial intracerebral infarction or haematoma, who were admitted to a rehabilitation clinic for retraining motor skills and self-care abilities, were eligible. Patients who on admission already walked safely or those who were on medication or had non-stroke-related sensorimotor deficits that could interfere with postural regulation were excluded. Also those patients who had concomitant cognitive or psychiatric problems that impaired the ability to follow simple verbal instructions were excluded. Thirty-nine patients with stroke were included over a two year period, 2 of whom were lost to follow-up. One patient developed severe secondary seizures and another patient had to be discharged prematurely because of insurance problems. Thus, an inception cohort of 37 patients was formed.

Table 2: Biological and clinical characteristics of the total group of patients with stroke (N=37) and of the subgroup of patients with at least 5 hits during the weight-shifting task throughout the follow-up period (N=25)

Characteristics	N = 37	N = 25
Age (range) (y)	61.6±12,9(27-82)	59.8±11.9(34–82)
Time post stroke (range) (wk)	10.0±5.4(3.3-24.1)	10.0±5.7(3.3–24.1)
Gender (men/women)	20/17	14/11
Type of stroke (infarction/hematoma)	30/7	22/3
Hemisphere of stroke (left/right)	13/24	7/18
Sensibility (disturbed/normal)	24/13	16/9
Ankle clonus (present/absent)	19/18	14/11
Trunk control (disturbed/normal)	22/15	16/9
Visuospatial hemineglect (present/absent)	16/21	10/15

Note. Values are mean ± standard deviation (range) or N

All patients received a standard rehabilitation program for 12 weeks after inclusion, consisting of individual and group sessions of physiotherapy and occupational therapy for at least 2 hours per day. Age, stroke type (infarction or haematoma), location (left or right hemisphere), and time post stroke at study entry were recorded based on the neurological records including computed tomography or magnetic resonance imaging scanning. Independent qualified members of the rehabilitation team, who were not actively involved in this study, conducted a standardized physical and neuropsychological examination at study entry. The physical examination provided data for lower-limb motor selectivity, sensibility, reflex activity, and trunk control. The lower-limb motor selectivity was scored according to the 6 motor stages defined by Brunnstrom[31,32]: I, flaccid paralysis; II, increased muscle tone without active movement, III, increased muscle tone with active movements mainly in rigid extension synergy, IV, increased muscle tone with alternating gross movements in extension and flexion synergies; V, muscle tone normalization with some degree of selective muscle control; and VI, normal muscle tone and control. The lower-limb sensibility score was obtained by testing position sense at the affected ankle joint in 3 different angles of dorsi- and plantarflexion by mirroring with the nonparetic side. The lower-limb sensibility was scored as 'disturbed' if the patient made more than one mirroring error. The lower-limb reflex activity was assessed by imposing a fast passive dorsiflexion motion at the affected ankle joint. Ankle clonus was present if the number of calf muscle contractions was greater than one during sustained dorsiflexion. The patient's trunk control was assessed with the sitting balance item of the Trunk Control Test[33]. Control was rated as 'disturbed' if the patient was unable to stay up sitting on the edge of a bed, feet off the ground, for 30 seconds.

Neuropsychological examination consisted of a letter cancellation test (the Dutch O-search test), the line bisection test from the Behavioural Inattention Test[34], and the first 6 items of the block design subtest of the Wechsler Adult Intelligence Scale (WAIS)[35]. The patients were considered to have visuospatial hemineglect when they showed abnormal lateralization in at least 2 of the 3 neuropsychological tests, that is, at least 10% fewer cancellations on the affected side in the O-search test, fewer than 7 of 9 points in the line bisection test, and more than 1 mistake in the WAIS block design subtest. All patients gave their informed consent after receiving both verbal and written information about the study. Approval was obtained from the institutional Ethics Committee.

Equipment Standing balance was assessed using a force platform consisting of 2 separate aluminum plates, each placed on 3 force transducers[a] (hysteresis and nonlinearity, <1%) that recorded the vertical ground reaction forces[13]. Signals were processed by 6 direct-current amplifiers[b] (nonlinearity, <0.1%) and first-order low-band pass filters with a cut-off frequency of 30Hz. Data were stored after a 12-bit analog-to-digital conversion at a sampling rate of 60 Hz. By means of digital moment-of-force calculations, the point of application of the resultant of the ground reactions in a 2-dimensional transverse plane was determined. The calculations were done for each sample, with a maximum error of ± 1 mm in the lateral and anteroposterior (AP) directions. The coordinates of this center of pressure (COP) were passed through a digital, low-band pass, 6-Hz Fourier filter to eliminate high-frequency components arising from noise.

For safety purposes, two parallel support bars were placed on each side of the force platform. During the eyes-closed condition, patients wore a pair of closed dark goggles. To provide visual COP feedback during the weight-shifting task, a 15-inch color monitor was placed slightly below eye level on a height-adjustable table 1 m in front of the patient while standing on the force platform.

Procedure Five assessments were made over a period of 12 weeks. The first assessment took place as soon as a patient was able to stand without assistance for 30 seconds or more (S). The same assessments were repeated 2 (S+2),4 (S+4), 8 (S+8), and 12 weeks (S+12) later. The timing of each patient's first assessment was indicated by the individual capability of standing without assistance (ie, prolonged active knee and hip extension at the paretic body side, to prevent limb collapse and abnormal trunk flexion during standing).

First, at all assessments, patients' walking ability was rated according to the FAC by the principal investigator (MdH). Then, a posturographic procedure was completed. Patients stood barefoot on the force platform with their arms alongside their trunk, if possible. Their feet were against a fixed foot frame, without providing any support, with the medial sides of their heels 8.4 cm apart and each foot placed with toes outward at a 9° angle from the sagittal midline. Before the first posturographic assessment, the base of support (BOS) was determined in both the lateral (ie, the distance between the heads of the fifth metatarsal bones of both feet) and the AP (ie, the distance from the rear of the heel to the tip of the great toe) directions while standing on the force platform. In addition, the distance between the anterior borders of the distal tibiae was assessed to obtain a measure of the individual 'stance width' (see figure 1).

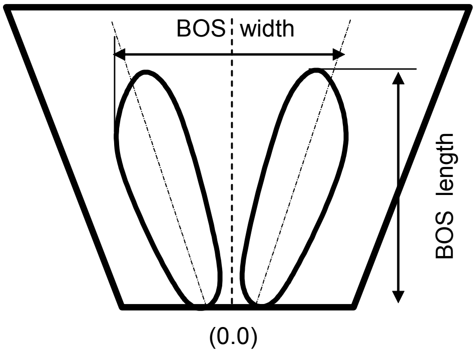

Figure 1. Foot placement on the dual-plate force platform

Every balance assessment consisted of 2 consecutive test series. Each test series incorporated 4 quiet-standing tasks and 1 weight-shifting task in a fixed sequence; this sequence was reversed during the second test series. The data of quiet-standing tasks are recorded for 30 seconds in each of the 4 conditions: (1) facing a screen with black and white horizontal bars (eyes open [EO]), (2) while performing a concurrent arithmetic task (dual task [DT]), (3) while looking at the same visual texture with a vertical black bar as a visual midline reference (visual reference [VR]), and (4) while wearing a pair of closed dark goggles (eyes closed [EC]). During these tasks, patients were instructed to stand as still and symmetrical as possible. The weight-shifting task required voluntary 'rhythmic' loading and unloading of both the paretic and nonparetic leg using visual COP feedback. The actual COP position was displayed in real time (lag time approximately 0.016 sec) and real-size on the monitor as a black cursor. Two stationary squares (30 x 30 mm) were presented at either side of the virtual vertical, the latter corresponding to the body's sagittal midline. The lateral position of the centers of the squares was individually set at 15% of the stance width. In this way, weight bearing of approximately 65% on each leg was required to bring the cursor to the middle of the corresponding square. In the AP-direction, the centers of the squares were positioned at 40% of the length of support from the rear, corresponding to the average COP position in the sagittal plane in healthy subjects[36]. The target square in which direction weight had to be transferred was indicated by filling it up with the color yellow, whereas the non-target square was filled up with the color blue. Subjects had to maintain their COP at least 1 second within the target square to make a 'hit'. As soon as a hit was made, the contralateral square became the target and turned into yellow. The first target was randomly assigned by the computer. Subjects were instructed to start from a comfortable position and to make as many weight shifts as fluently as possible. Because no fixed rhythm was imposed, each subject determined his/her own speed and precision. The weight-shifting task was practiced for several minutes before its first performance, until each subject showed an optimal understanding and individual ability.

A 1-minute rest was given after each balance test, whereas a longer pause was allowed between the 2 test series. In some patients, especially during the early assessments, the physiotherapist assisted in foot placement and heel loading just before the start of recording. Nevertheless, no physical contact from the physiotherapist or from the support bars beside the platform was allowed during the data collection.

Data analysis The root mean square (RMS) of the COP velocities (VCOP) in either direction (mm/sec) was selected as the primary measure of postural control or stability during the quiet-standing recordings, because it integrates COP amplitude changes and COP frequency shifts[13]. In addition, weight-bearing asymmetry during quiet stance was expressed as the lateral deviation of the mean COP position (PCOP) from the sagittal midline toward the nonparetic leg as a percentage of the BOS width. As for the weight-shifting task, the number of hits (N) in 30 seconds was selected as a measure of the speed of weight shifting. To assess the precision of weight shifting, an 'imprecision' measure (*I*P) was calculated[37]: the total COP displacement in the lateral direction (mm) was divided by the number of full weight shifts (N-1) to obtain the average lateral COP displacement per weight shift (mm). Because the inter-target distance was proportional to the individual stance width, this measure was then normalized to the average stance width of all participants according to the following equation:

$$P = \frac{\left(\frac{\sum_{i=1}^{1799} \left| X_{i+1} - X_i \right|}{N-1}\right) * \overline{R}}{R_{ind}} \qquad \text{(equation 1)}$$

where X_i = lateral COP coordinate, i = time sample, N = number of hits, $\overline{R}$ = average stance width, and R_{ind} = individual stance width. Whereas the speed of weight shifting could be determined for all tests, the imprecision was only calculated for those recordings with at least 2 full weight shifts in either direction (i.e. N > 4).

For each balance test, the comparable parameters derived from the 2 test series were averaged for statistical analysis. However, if just one of two weight-shifting recordings resulted in more than 4 hits, only this recording was used to determine the imprecision.

Longitudinal associations between posturography parameters and the FAC were evaluated using Generalized Estimating Equations (GEE)[38]. GEE analysis is a linear regression analysis which takes into account the dependency of the observations within one patient, and which allows all available longitudinal data to be used. An exchangeable within-group correlation structure was used. Force-platform parameters were entered into the GEE model as the independent variable, with FAC as the dependent variable. The longitudinal relationship between FAC and the independent variable can be described by equation:

$$FAC_{it} = \alpha + \beta\,(\text{force-platform variable})_{it} + \varepsilon_{it} \qquad \text{(equation 2)}$$

where FAC_{it} are FAC values for subject *i* at time *t*, α is the intercept (constant), β is the regression coefficient for the independent force-platform variable and ε_{it} is the 'error' for subject *i* at time *t*. GEE analysis was performed with STATA (version 7)[c]. The explained variance of the model was estimated from the standard deviation of the model (scale parameter, S_{model}) and the standard deviation of the outcome variable calculated over all available data (S_{FAC}) by using the following equation:

$$F_{it} = 1 - (S^2_{model} / S^2_{FAC}) \qquad \text{(equation 3)}$$

RESULTS

Complete data on quiet standing was obtained in all 37 patients with stroke. Data on weight shifting was obtained in 36 patients due to an error in the data collection of one subject. Because 11 of these patients failed to make the minimum of 5 hits in at least one assessment, the imprecision measure was analysed only for a subgroup of 25 patients. This subgroup did not show significant differences in their biological or clinical characteristics compared to the total group of patients with stroke. The main biological and clinical characteristics of the total group (N=37) and of the subgroup (N=25) are listed in table 2.

Figure 2 shows that 81% of the patients were able to walk independently on level ground (FAC score 4 or 5) after 12 weeks of standard rehabilitation therapy. The median FAC score improved by 2 points from 2 (range 1-4) at the start to 4 (range 1-5) at the end of the follow-up period.

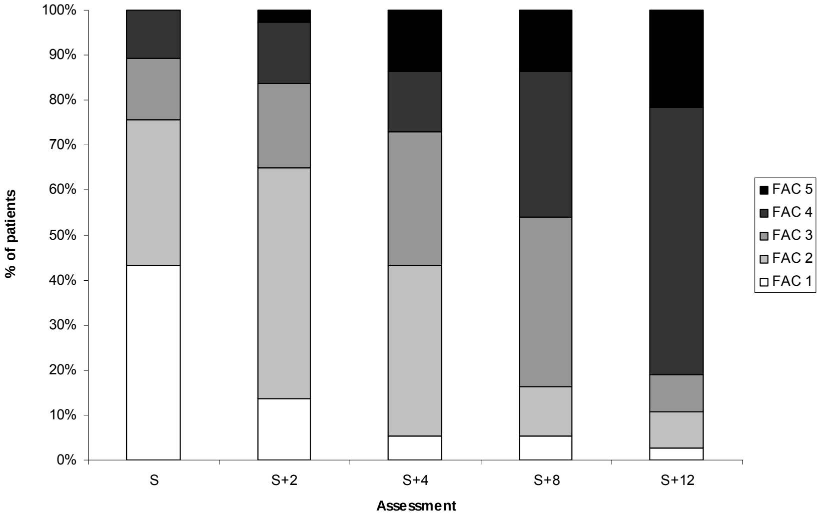

Figure 2: The FAC score distribution for all patients with stroke (N=37) at all follow-up assessments. S = start of standing balance training.

Table 3: Selected posturographic parameters at the start (S) and at the end (S+12) of the follow-up period

	N	Condition	S	S + 12
PCOP	37	EO	12.6 (9.5 – 15.7)	9.2 (7.1 – 11.4)
(% BOS width)	37	DT	16.4 (12.9 – 20.0)	11.2 (8.8 – 13.7)
	37	VR	11.9 (8.9 – 14.8)	8.5 (6.0 – 11.0)
	37	EC	13.0 (9.5 – 16.5)	10.0 (7.1 – 12.8)
VCOP lateral	37	EO	18.3 (15.2 – 21.3)	12.9 (10.3 – 15.6)
(mm/s)	37	DT	20.2 (16.9 – 23.4)	13.9 (10.8 – 17.1)
	37	VR	19.3 (15.9 – 22.8)	12.9 (10.1 – 15.7)
	37	EC	25.4 (20.4 – 30.4)	16.7 (12.6 – 20.7)
VCOP AP	37	EO	23.4 (19.1 – 27.6)	19.7 (15.2 – 24.1)
(mm/s)	37	DT	25.9 (20.1 – 31.7)	22.3 (17.1 – 27.5)
	37	VR	24.1 (19.1 – 29.1)	18.9 (15.0 – 22.9)
	37	EC	32.1 (25.6 – 38.6)	26.0 (20.6 – 31.3)
Hits (number)	36	-	6.9 (5.8 – 8.0)	9.2 (7.9 – 10.4)
Imprecision (mm)*	25	-	154 (124.3 – 183.7)	116.4 (98.6 – 133.9)

NOTE. Values are means and 95% confidence intervals. Abbreviations: EO = eyes open, DT = dual task, VR = vertical midline reference, EC = eyes closed; BOS = base of support. * Imprecision = normalized average COP displacement per weight shift in the frontal plane. Source: de Haart et al.[6,9]

In the same time period, the patients with stroke improved their lateral and AP postural stability, their weight-bearing symmetry, and their weight-shifting capacity in terms of both speed and precision (see table 3)[6,9].

Table 4: GEE models examining the association between force-platform measures and FAC

	N	Condition	Regression coefficient (ß)	SE	p-value
PCOP	37	EO	-.001	.006	.861
(% BOS width)	37	DT	-.010	.006	.106
	37	VR	-.002	.006	.683
	37	EC	-.017	.006	.004
VCOP lateral	37	EO	-.028	.014	.05
(mm/s)	37	DT	-.021	.014	.135
	37	VR	-.024	.012	.037
	37	EC	-.020	.008	.013
VCOP AP	37	EO	-.011	.008	.185
(mm/s)	37	DT	-.004	.007	.602
	37	VR	-.006	.007	.34
	37	EC	-.010	.006	.188
Hits (number)	36	-	.041	.019	.032
Imprecision (mm)*	25	-	-.002	.001	.102

Abbreviations: EO = eyes open, DT = dual task, VR = vertical midline reference, EC = eyes closed, BOS = base of support, * Imprecision = normalized average COP displacement per weight shift in the frontal plane. Source: de Haart et al.[6,9]

To examine the longitudinal relationship between the FAC and the selected posturographic parameters, a linear GEE model was estimated for each parameter separately (quiet-standing VCOP lateral, VCOP AP and PCOP; weight-shifting hits and imprecision) (see table 4).

As for quiet standing, negative associations with the FAC were found for VCOP lateral during the EO, VR and EC conditions, each condition explaining 37% of FAC variance. PCOP was also negatively associated with the FAC, explaining 35% of its variance, however, only with regard to the EC condition. No associations were found between the VCOP in the AP direction and the FAC. As for voluntary weight shifting, only the number of hits showed a positive association with the FAC, explaining 32% of its variance.

DISCUSSION

Of all selected posturographic parameters derived from unperturbed standing and voluntary weight shifting, those reflecting lateral postural stability in stance showed the strongest association with the FAC in patients with a first-ever supratentorial stroke during their postacute rehabilitation. The strength of this association was not affected by visual deprivation, which suggests that it reflects a common lack of efferent control of frontal-plane balance during standing and walking. In an earlier study based on the same cohort of patients, it was shown that the greatest potential for quiet-standing control was reflected in the same measure for lateral postural stability (i.e. VCOP lateral)[6]. The present finding that also lateral weight-shifting capacity was associated with the independency of gait is coherent with earlier findings that this capacity shows equally substantial improvements during rehabilitation and increasingly strong associations with quiet-standing stability (explained variance approximately 50%)[9].

The results of the present study are corroborated by those reported by Titianova et al.[18] who found that maximum walking velocity in patients with chronic stroke was quite strongly related to their lateral COP displacement while standing with eyes open or closed (r_s = -.68, explained variance 46%). Although the strength of this correlation seems somewhat greater than that found in the present study, these values are not directly comparable since gait velocity is a continuous variable, whereas the FAC score is an ordinal one. It must be acknowledged, however, that both values are low enough to conclude that both ambulation velocity and dependency must be determined also by other factors than those reflected in the selected posturographic measures, for instance by the ability to make adequate stepping responses during gait perturbations or by the many sensory and cognitive aspects of gait control[24]. Nevertheless, the associations found in this study indicate that both static and dynamic postural instability in the frontal plane are important determinants of gait dependency following stroke.

The COP velocity in the lateral direction mainly reflects the variability in weight bearing on either leg during quiet biped stance. Both automatic and voluntary loading and unloading of the legs are primarily regulated by the coordinated activity of hip abductors and contralateral adductors and vice versa[39-40]. In the case of a hemiparesis, compensatory activity of the nonparetic leg can be used to maintain lateral postural stability[41-42]. In a recovery study with postacute patients with stroke, Kirker et al.[43] have shown that the hip abductors and adductors at the nonparetic side first try to compensate for the paretic hip muscles to withstand sideways pushes in either direction. In the case of recovery, the paretic gluteus medius muscle becomes active to resist perturbations towards this side and, eventually, the paretic adductor responds to perturbations towards the nonparetic side, although often with delayed onsets in both muscles. Because recovery always followed this specific pattern, it can be assumed that better muscular control at both the paretic and nonparetic hip may be responsible for improved lateral postural stability, depending on the stage of recovery. Hence, improved coordinated activity of bilateral hip abductors and adductors may well be the common physiological mechanism behind the associations between lateral standing balance, lateral weight shifting and gait.

A reduction in the lateral deviation of the mean COP position (PCOP) during unperturbed standing (ie, improved weight-bearing symmetry) showed a significant association with higher FAC scores. Although this association was significant only for standing during visual deprivation, it is interesting because the PCOP showed no association with any of the other posturographic parameters[9]. Apparently, weight-bearing asymmetry contributes unique information compared to the ‘dynamic’ parameters in determining gait dependency, although probably only when assessed under complex conditions.

CONCLUSIONS

Both static and dynamic postural instability in the frontal plane and, to a lesser degree, lateral weight-bearing asymmetry are associated with ambulation dependency in the postacute phase of stroke. These findings suggest that standing balance training, as a prerequisite for independent walking, should specifically focus on these lateral aspects of postural control after supratentorial stroke. Future intervention studies should further substantiate this conclusion.

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SUPPLIERS

[a] Load cells, type LM-100KA, Kyowa Electronic Instruments Company, Limited, Chofu-Higashiguchi Building 2F, 45-6, Fuda 1-chome, Chofu, Tokyo 182, Japan.

[b] RMP DC-amplifier, type MBP 6218, Elan Schaltelemente GmbH, Holzheimer Weg 50, D-4040 Neuss 1, Germany.

[c] STATA (2001). Stata reference manual, release 7. StataCorp, College Station, TX: Stata Press.

6

Effects of Visual Center of Pressure Feedback on Postural Control in Young and Elderly Healthy Adults and in Stroke Patients

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Mylène C. Dault, PhD, Mirjam de Haart, MD, Alexander C.H. Geurts, MD, PhD, Ilse M.P. Arts, MD, Bart Nienhuis Med Eng

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ABSTRACT

The goal of this study was to compare young and elderly healthy individuals and elderly stroke patients in their capacity to use visual CP feedback (VF) in controlling both quiet standing and weight shifting and to assess their sensory re-weighting when this VF is withdrawn. A total of 40 participants were involved in this study. Participants were asked to either quietly stand on a force platform for a period of 45 seconds with eyes open (EO), using visual feedback (VF) or without visual feedback (No VF) or to perform a dynamic weight shifting task while using VF or No VF. During the quiet standing trials with VF, only the young (YO) were able to decrease the amplitude and increase the frequency of their sway in either plane. Removal of the VF resulted in a 'destabilizing' effect in both healthy elderly (EL) and stroke patients (ST) in the sagittal plane. With regard to the dynamic task, both the YO and EL were generally more successful at weight shifting in terms of speed and control when compared to the ST. Yet, when VF was removed, only the YO were able to largely maintain speed and precision of control. Hence, providing or removing visual CP feedback during quiet standing or removing VF during visually controlled weight shifting can discriminate healthy young participants from healthy elderly, but does not clearly discriminate healthy elderly from stroke patients in the same age group. Results revealed that sagittal plane imbalance in healthy elderly and stroke patients may be largely due to the effects of aging, whereas frontal plane imbalance is much more specific for the postural problems associated with stroke.

INTRODUCTION

In the current literature many hypothesis are being put forward in order to understand how postural control is maintained. It is thought that postural control is largely maintained by using three sensory inputs: visual, somatosensory, and vestibular. However, little information is known as to how the central nervous system is able to integrate all this information[1]. It was found by Gatev et al.[2] that changes in stance width relate to changes in postural strategy, e.g. in the sagittal plane, normal-width stance is controlled by ankle strategy whereas narrow-width stance is controlled by hip strategy. When sensory information was modified by removing vision, no changes were found, in postural sway suggesting that the central nervous system is able to adapt to such modifications without altering postural control by sensory re-weighting[2]. Sensory re-weighting can be defined as the ability to adapt to various conditions by giving more importance to certain sensory information and less importance to other[1]. Indeed, Oie et al.[1] recently found, by imposing both visual and proprioceptive manipulations, that it is the sensory weighting that is modified and not the efferent postural control strategy. As the central nervous system ages, the sensory systems become less sensitive and balance becomes more difficult to maintain which is one of the reasons that falls may occur[3-5]. Research has shown that older individuals show increased sway when visual information is altered suggesting greater visual dependency[6-7]. When standing quietly, individuals can use visual information from a fixed visual environment to reduce postural sway. When visual information is altered such as with moving visual scenes, postural sway is increased[7]. This alteration of visual information requires re-weighting of the sensory systems. Elderly individuals seem to have greater difficulty in this sensory re-weighting process[7-8]. Hence, modifying visual information, by adding or removing certain aspects essential to postural control, could possibly be used as a tool to evaluate sensory integration in various populations.

Following stroke, postural control deficits are common. These balance deficits are demonstrated by increased postural sway[9-11] as well as asymmetrical standing[9-10,12]. Many studies have examined the use of visual feedback in rehabilitation subsequent to stroke as a training tool[9-10, 13-15]. It is thought that by giving patients additional visual information, they will become more aware of the body's displacements and orientation in space. Stroke patients are asked to maintain a symmetrical stance by using visual information that is projected on a screen, which presents their centre of pressure (CP). Results from these studies have revealed benefits with visual feedback training, but these changes were no more pronounced than those through regular physical therapy[10,13-14]. Visual CP feedback may result for example, in acute improvements in weight bearing symmetry, but this is usually characterized by the absence of long-term effects[9,16].

The goal of this study is to examine the ability of three different population groups (young, elderly and stroke) to use visual feedback information to influence postural control during both quiet standing and weight shifting. This ability was investigated not so much from a therapeutical, but rather from a diagnostic perspective to assess their level of sensory integration. Contrary to other studies that have used standardized visual feedback tasks, this study used an individualized visual CP feedback task that was designed such that boundaries used in the visual CP feedback were proportional to each participant's balance ability. It was thought that by using a feedback task that was individualized to each participant's balance ability, we would be able to better evaluate sensory integration capacity. In addition to this we included experimental conditions where visual CP feedback was removed during the trial to examine if participants were able to maintain the same level of standing and weight-shifting control by integrating sensory information from all sensory systems instead of focusing only on the visual feedback task.

METHODS

Participants *Healthy participants* A total of 30 healthy individuals participated in the study. Fifteen young individuals (mean age = 26.5 ± 4.0) were included in the young healthy group. Fifteen elderly individuals (mean age = 64.7 ± 6.0) formed the elderly healthy group. Selection criteria were the following: no orthopaedic or neurological deficits and no unexplained balance problems or visual deficits other than adequately corrected loss of visual acuity. Because one of the experimental conditions required the ability to distinguish the colour yellow from the colour blue, colour perception was verified by a colour distinction test in which the participants stated which square of two appearing on a computer screen was yellow by answering left or right. After each answer a new series of squares appeared up to a total time of 60 seconds. Participants that could not distinguish the yellow square from a blue square without errors were excluded from the study.

Stroke Patients Ten patients with a first hemispheric intra-cerebral infarction or haematoma, who were admitted as inpatients to a specialized neurorehabilitation unit for retraining (gross) motor skills and self care abilities, participated in the study (mean age = 57.8 ± 10.8). At the time of the experiment, their time post-stroke was on average 11.86 weeks (± 4.71) (range: 4.40 – 20.90 weeks). Patients who on admission already walked safely as well as those with medication or non-stroke related sensory or motor impairments that could interfere with their postural control were excluded from the study. Patients with visual field deficits, insufficiently corrected loss of visual acuity, diplopia and or visuospatial hemineglect were excluded as well. The same colour distinction test as in the healthy participants groups was administered to the stroke patients. Age, gender, type (infarction or haematoma), localization (left or right hemisphere), and time post onset at study entry were registered (see Table 1). All participants gave their informed consent after having received information about the study and the potential risks involved. Approval was obtained from the institutional ethical committee.

Table 1. Description of stroke patients (N=10)

Patients	Age	Gender	Type	Location	Sensibility	Motor score**	Clonus	Neglect
1	65	F	infarct	RH	D	IV	-	Pre
2	78	M	infarct	RH	D	VI	-	Pre
3	38	F	infarct	RH	N	VI	+	Pre
4	51	F	infarct	RH	N	IV	+	Pre
5	53	M	infarct	RH	D	II	+	Pre
6	57	M	infarct	RH	D	IV	+	Abs
7	59	F	infarct	RH	D	V	+	Pre
8	56	M	infarct	STEM*	N	VI	-	Abs
9	53	F	infarct	RH	N	II	+	Abs
10	68	M	infarct	LH	N	V	-	Abs

Infarct = infarction; STEM = brain stem; RH = right hemisphere; LH = left hemisphere; D = disturbed; N = normal; Abs = absent; Pre = present. *Predominantly left hemiplegia, ** Max VI (see text)

Clinical examination In the healthy young and elderly group a short questionnaire was taken to verify the absence of orthopaedic, neurological and visual deficits. In the stroke patients a standardized physical examination was done by a rehabilitation physician. The physical examination consisted of (1) a lower limb motor selectivity score according to the 6 motor stages defined by Brunnstrom[17] (I=flaccid paralysis; II=increased muscle tone without active movement; III=increased muscle tone with active movements mainly in rigid extension synergy; IV=increased muscle tone with alternating gross movements in extension and flexion synergies; V=muscle tone normalization with some degree of selective muscle control ; VI=normal muscle tone and control); (2) a lower limb sensibility score by testing position sense at the affected ankle joint in three different angles of dorsi- and plantar flexion by mirroring with the unaffected ankle while patient is supine, and the affected leg is slightly lifted by investigator (''disturbed'' if > 1 mirroring error); (3) a lower limb reflex activity score by eliciting fast dorsiflexion at the affected ankle joint while patient is in the same position as in former test (''ankle clonus'' if ≥ 2 calf muscle contractions with sustained dorsiflexion); (4) a trunk control score by determining the sitting balance item of the Trunk Control Test[18] (''disturbed'' if unable to stay up sitting on edge of bed, feet off ground, for 30 sec). Patient characteristics and results of clinical examination are presented in table 1.

Equipment Postural control was measured by using a force platform consisting of two separate aluminium plates, each placed on three force transducers (hysteresis and non-linearity < 1%) recording the vertical ground reaction forces[19]. Signals were processed by six - DC amplifiers (non-linearity < 0.1%) and first-order low-pass filters with a cut-off frequency of 30 Hz. Data was stored after a 12-bit AD conversion at a sampling rate of 60 Hz. By means of digital moment-of-force calculations, the point off application of the resultant of the ground reaction forces was determined in a 2-dimensional transverse plane for each sample, with a maximum error of ± 1 mm in the lateral (LAT) and antero-posterior (AP) directions. The coordinates of the CP displacements were passed through a digital, low-pass, Fourier filter with a 6 Hz cut-off frequency was used to eliminate high-frequency components due to noise. For safety purposes, two parallel support bars were placed beside the force platform. A white screen (300 cm wide x 260 cm high) was placed at a distance of approximately two meters and covered most of the visual field. Real-time, real-size visual CP feedback was provided in the conditions with feedback through a computer screen (35 cm wide) that was placed 1 m in front of the participants while standing on the dual-plate force platform. Real-size indicates a 1:1 ratio between the displacement of the CP and the displacement of the black cursor on the screen. The lag time between movement of the CP and the cursor was about 16 msec.

Procedure During posturography the participants stood barefoot on the force platform with their arms, if possible, alongside their trunk and their feet against a fixed foot frame (with the medial sides of their heels 8.4 cm apart and each foot placed with toes outward at a 9° angle from the sagittal midline). Prior to testing and while standing on the platform, the maximum distances of the base of support (BOS) were determined in both the LAT (width of support) and the AP (length of support) directions as well as the reference width which corresponded to the distance between the anterior borders of the distal tibiae while standing on the platform.

Experimental conditions Three 45-second static balance conditions were conducted (1) facing a white screen (eyes open (EO)), (2) while using visual

CP feedback from a computer screen (VF) and (3) without visual CP feedback (No VF). For the EO condition participants were simply asked to stand quietly with arms at their side while looking straight ahead at a white screen. The VF-tasks consisted of asking participants to maintain their CP (represented by a small black cursor) within a square that was presented on the computer screen. The width and the height of the square were adjusted to the RMS of their individual spontaneous sway amplitude in the AP and LAT directions respectively, calculated from the first three eyes open trials. In the AP direction, the middle of the square was positioned at 40% of the length of support from the rear. During the No VF task, the black cursor, representing the CP, disappeared after the first 15 s and the participants were instructed to try and maintain the same control strategy as during the VF task. For the remainder of the trial, participants were still looking at the square on the computer screen but without having the black cursor representing their CP. During all static conditions, the participants were asked to stand as still and symmetrically as possible.

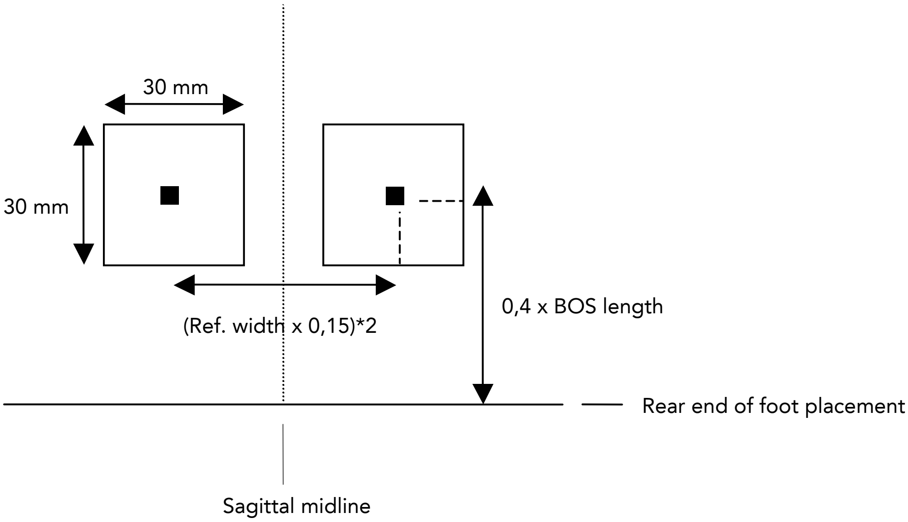

Figure 1. Scheme of placement of the target squares for the dynamic tasks with regards to the reference width.

In addition, two 45-second dynamic balance tasks were performed (1) dynamic weight shifting with visual CP feedback (DVF) and (2) weight shifting without visual CP feedback (No DVF). During these dynamic tasks, participants were asked to shift their CP from one square to another presented on the computer screen placed in front of them. They were instructed to make as many correct weight shifts per trial as fluently as possible. The size of the squares was fixed at 30 x 30 mm and the middle of each square was placed at 15% of the reference width at each side of the sagittal midline and at 40% of the length of support from the rear (see Fig. 1). The position of each square was such that approximately 15% extra weight had to be born on each leg to reach the middle of the target. The target square was yellow versus the non-target square being blue. Participants were instructed to shift their CP towards the yellow square. When they were able to maintain their CP inside the yellow square during 1second, the colour of the square would change to blue and they had to shift their CP to the other square that was now the yellow target, and so on. Participants could follow the movements of their CP with the help of a black cursor appearing on the screen for the whole trial during the DVF task. For the No DVF task, participants were asked to move their CP from one square to the other, this time, however, the black cursor disappeared after the first 15 seconds.

All experimental tasks were repeated twice, except for the eyes open task which was performed four times, i.e. three times at the beginning and once at the end. The three times at the beginning allowed us to calculate the average RMS value to determine the size of the visual feedback square. The last trial of the eyes open task was placed at the end to control for fatigue effects since the three other trials were always performed at the beginning; the average of all 4 trials was included in the statistical analysis. All other experimental tasks were presented in a completely random order for both the static and dynamic tasks combined. Each task was preceded by a 5-second anticipation period followed by a low-frequency starting tone. A 60 second rest was given between each trial. If necessary, the researcher helped the patients with foot placement and heel loading by muscle tone inhibition prior to data collection. No physical contact from the researcher or from the support bars beside the platform was allowed during the registrations.

Data analysis During the no visual feedback tasks (no VF and no DVF) the cursor disappeared after 15 seconds. Hence, only the last 30 s were included in the analysis for all experimental conditions. In this way the conditions could be easily compared, because they all lasted 30 seconds.

Static balance measures Three (interrelated) measures of CP displacements were taken in the AP and LAT directions, separately. Amplitude variability was determined by calculating the root mean square (RMS) of the CP displacements (Acp). After a first-order differentiation, the RMS was calculated once more as a measure of velocity variability (Vcp). From these parameters, the mean frequency (Fcp) was estimated following the approximation proposed in Geurts, et al.[19]:

$$Fcp = \frac{Vcp}{2\pi Acp}$$

Together these 3 parameters provide estimations of body sway (Acp), regulatory frequency (Fcp) and the efficiency of the postural regulation (Vcp), the latter two being most strongly related to the corrective ankle moments applied at the support surface.

Dynamic balance measure The number of correct 'hits' was recorded as a measure of the speed of weight shifting. An imprecision calculation was also performed. The imprecision measure was calculated in the following manner: first, the total CP displacement in the LAT direction in mm during the last 30s of each trial (n-1 where n = 1800 representing 30s at a sampling rate of 60 Hz) was divided by the number of hits to obtain the average distance per weight shift; second, because the distance between the squares was related to the individual reference width, this value was then normalized to the average reference width of all the participants by:

$$P = \frac{\left(\frac{\sum_{i=1}^{1799} \left| X_{i+1} - X_i \right|}{N-1}\right) * \bar{R}}{R_{ind}}$$

where X_i represents the LAT CP coordinate at time sample i, N represents the number of hits, $\bar{R}$ represents the average reference width and R_{ind} represents the individual reference width.

Statistical analysis All static CP measures (dependent variables) were first tested in a multivariate analysis of variance (two-way MANOVA) to examine main and interaction effects of Group (healthy young, healthy elderly and stroke) X Task (EO, VF, No VF), with repeated measures on the factor Task. As for the dynamic balance measures, a two-way ANOVA of Group (3) x Task (DVF, No DVF) was conducted with repeated measures on the factor Task. Where significant multivariate effects were detected, univariate follow-up procedures were conducted.

RESULTS

Due to technical problems, data from two stroke patients had to be excluded from the analysis for the VF and NoVF tasks (static task only). In

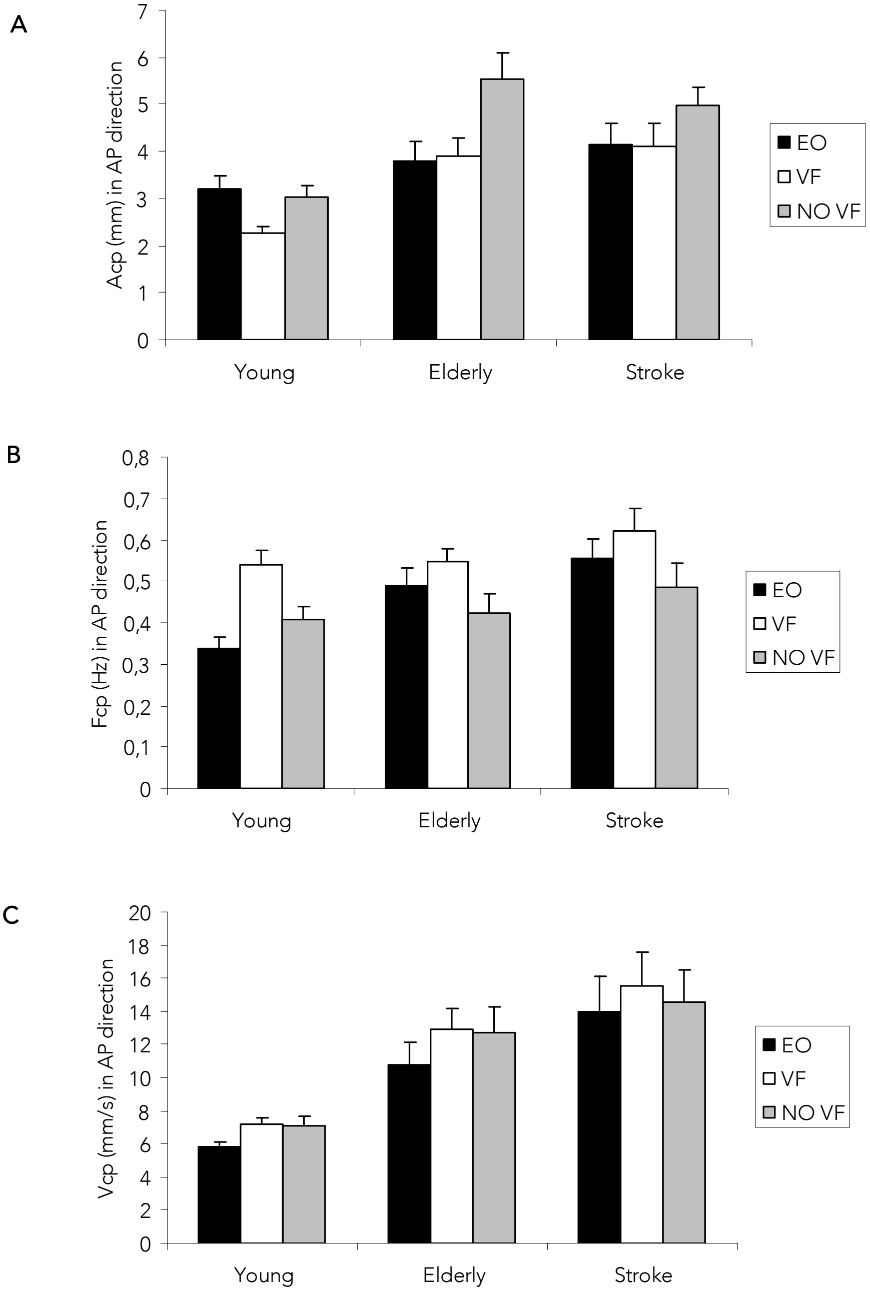

Figure 2. Mean and standard error values of Acp (A), Fcp (B) and Vcp (C) in the sagittal plane for static balance tasks (EO, VF and No VF) for all three groups of participants.

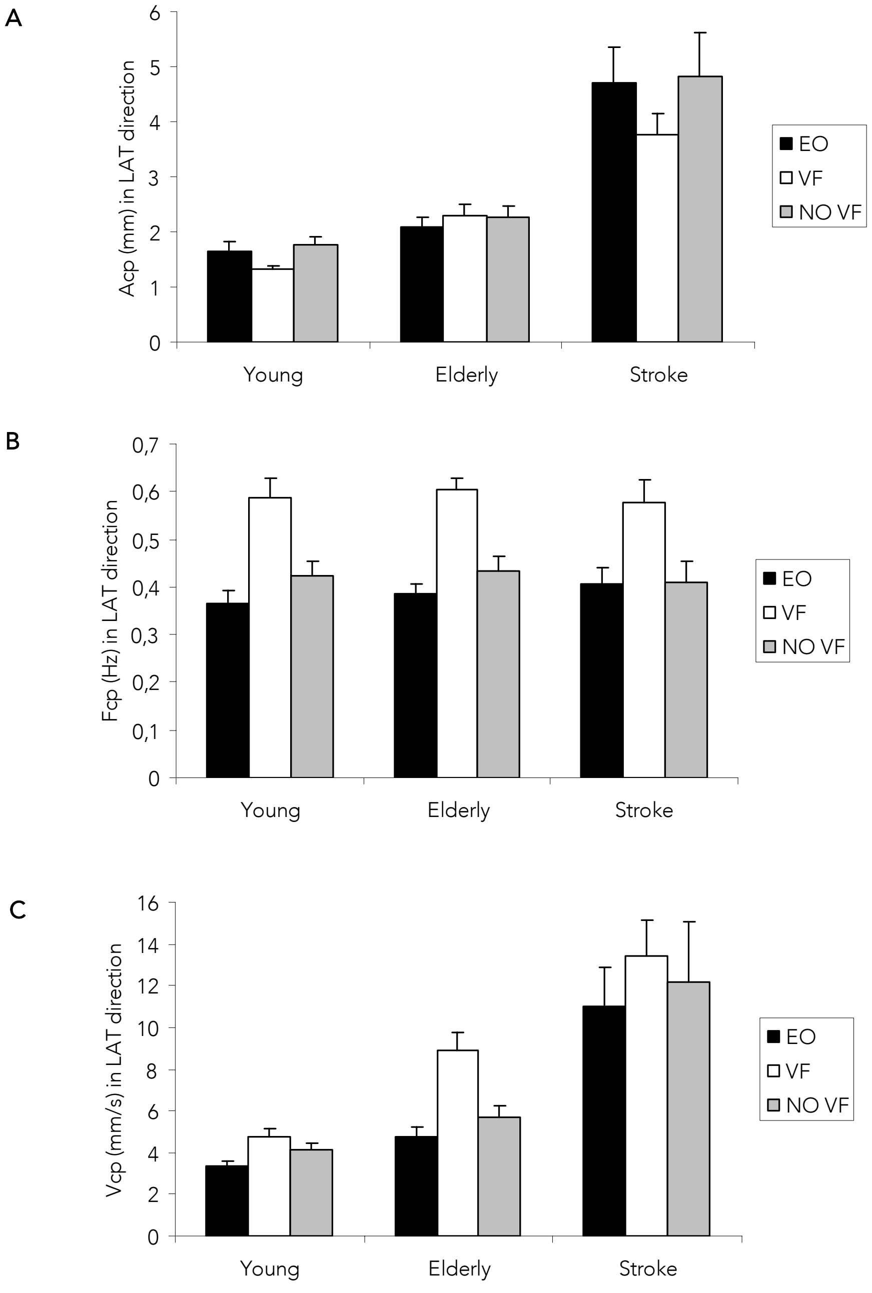

Figure 3. Mean and standard error values of Acp (A), Fcp (B) and Vcp (C) in the frontal plane for static balance tasks (EO, VF and No VF) for all three groups of participants.

addition, one stroke patient was not able to perform the NoVF task (static task only).

Sagittal plane balance Two-way MANOVA indicated that only the young were able to significantly reduce their sway amplitude by 29.2% with the addition of visual CP feedback (group x task interaction $F_{4,66}$=2.91, *P*<.05) (see Fig. 2A). This reduction in sway amplitude coincided with a marked increase in the mean frequency of 59.9% (group x task interaction $F_{4,66}$=3.77, *P*<.01) (see Fig. 2B). In contrast, the elderly and stroke patients were not able to reduce their sway amplitude with the VF (see Fig. 2A), although both groups showed a similar tendency towards a higher regulatory frequency (see Fig. 2B).

CP velocity showed evidence of greater imbalance in the stroke patients than in the elderly, and in the elderly more than in the young (main effect of group $F_{2,34}$=11.59, *P*<.0001). No significant interaction was found for CP velocity. All groups combined demonstrated a small, but significant increase in sway velocity in the VF and NoVF conditions compared to the EO condition (main effect of task $F_{2,33}$=9.92, *P*<.0001) (see Fig. 2C).
When visual CP feedback was taken away, a marked destabilization, i.e. an increase in sway amplitude, was seen in both the elderly (45.6%) and stroke patients (20.1%) (see Fig. 2A), which coincided with a (compensatory) decrease in the mean frequency of both groups when compared to the EO task (see Fig. 2B). In contrast, the young group maintained a slightly decreased amplitude and a moderately increased mean frequency with removal of VF compared to the EO task (20.8%) indicating a similar pattern as during the VF feedback task.

Table 2. Summary of results for the static task

		Task	Group	Group x Task
AP	Acp	$F_{2,33}$=8.60, *P*<.001	$F_{2,34}$=8.85, *P*<.0001	$F_{4,66}$=2.91, *P*<.05
	Fcp	$F_{2,33}$=18.36, *P*<.0001	NS	$F_{4,66}$=3.77, *P*<.01
	Vcp	$F_{2,33}$=9.92, *P*<.0001	$F_{2,34}$=11.59, *P*<.0001	NS
ML	Acp	$F_{2,33}$=10.69,*P*<.0001	$F_{2,34}$=31.55, *P*<.0001	$F_{4,66}$=5.76, *P*<.0001
	Fcp	$F_{2,33}$=56.59, *P*<.0001	NS	NS
	Vcp	$F_{2,33}$=44.24, *P*<.0001	$F_{2,34}$=18.37, *P*<.0001	$F_{4,66}$=4.34, *P*<.01

Frontal plane balance MANOVA revealed that, in contrast to the healthy elderly, both the young and the stroke patients were able to significantly reduce their sway amplitude by 20.7% and 20.3% respectively with the addition of visual CP feedback (group x task interaction $F_{4,66}$=5.76, *P*<.0001) (see Fig. 3A). Yet, the VF condition revealed a substantial increase in Fcp in all groups (main effect of task $F_{2,33}$=56.59, *P*<.0001) (see Fig. 3B). The healthy elderly most markedly increased their CP velocity by 86.8% with the VF when compared to the other groups (group x task interaction $F_{4,66}$=4.34, *P*<.01) (see Fig. 3C). Overall, CP velocity generally showed much higher values for the stroke patients compared to the elderly and young (main effect of group $F_{2,34}$=18.37, *P*<.0001).

All groups demonstrated the same type of pattern in the no VF as in the EO task for CP amplitude, frequency and velocity (see Fig. 3). A summary of all static results is presented in table 2.

Dynamic balance As shown in figure 4A, with the visual CP feedback, the stroke patients were able to perform only 9.2 successful hits compared to 12.0 and 13.7 for the elderly and the young group, respectively (main effect of group $F_{2,37}$=12.67, *P*<.0001). All groups were much less successful without visual feedback (main effect of task $F_{1,37}$=69.64, *P*<.0001). This effect was most pronounced in the stroke group (59.2% reduction) and in the elderly (44.0% reduction) and least in the young group (23.4% reduction). However, the group x task interaction did not reach significance ($F_{2,37}$=1.83, *P*=0.18).

A

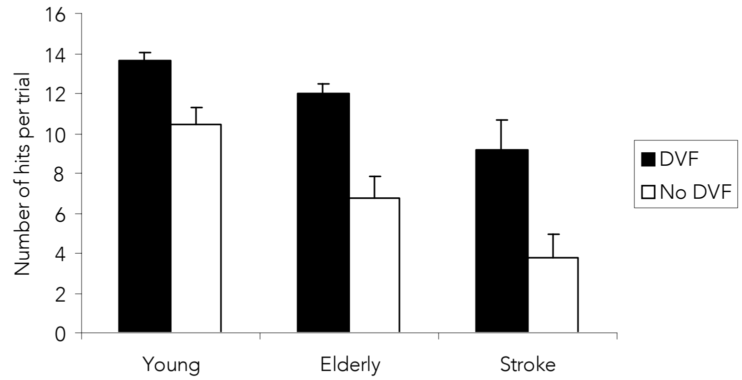

Figure 4A. Mean and standard error values of the number of successful hits for dynamic balance tasks (DVF and No DVF) for all three groups of participants.

As for the imprecision measure, figure 4B illustrates that the young and the elderly showed similar results with visual CP feedback (90.1 mm and 93.9 mm, respectively), but the stroke patients overshooted much further outside the boundaries of the square presented on the computer screen (267.1 mm) (main effect of group $F_{2,36}=4.38$, $P<.05$). Without visual CP feedback, all groups became less precise than with the visual feedback (main effect of task $F_{1,36}=10.54$, $P<.005$). Although this effect was more dramatic for the elderly and stroke group, who showed an increase of 330.74% and 125.95%, respectively compared to 72.83% for the young group, the group x task interaction again did not reach significance ($F_{2,36}=1.69$, $P=0.198$).

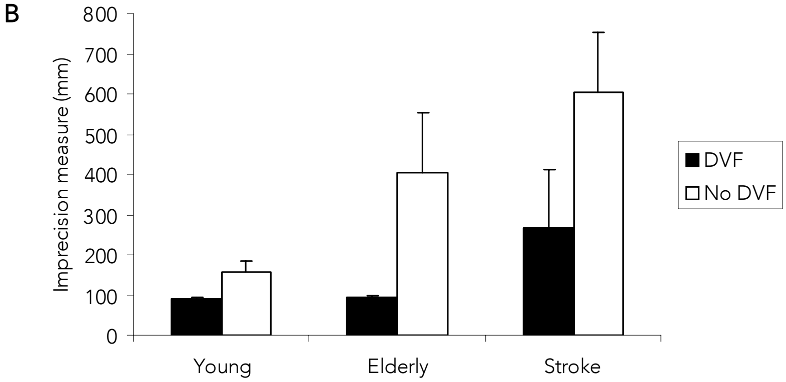

Figure 4B. Mean and standard error values of the imprecision measure for dynamic balance tasks (DVF and No DVF) for all three groups of participants.

DISCUSSION

The purpose of this study was to assess the differences between young individuals, elderly individuals and stroke patients in their capacity to integrate visual CP feedback for controlling static as well as dynamic balance. The effect of removing VF was tested to assess sensory re-weighting capacity. Providing and removing visual CP feedback during quiet standing discriminated between the young participants and the other groups, in particular for sagittal plane balance, by analysing their sway pattern in terms of CP amplitude, frequency and velocity. With VF, the young healthy participants were able to significantly reduce the amplitude and increase the frequency of their sway control in both the sagittal and frontal planes, while their CP velocity showed only a minimal increase. This change in efferent postural strategy was characterized by a "tighter" control of body sway through more rapid alternations in the direction of ankle moments, which is in accordance with the task requirements of the VF condition. In contrast, the elderly were not able to adapt sway control to the requirements task during the VF condition in either plane. The stroke patients, however, were able to modify at least their LAT sway as shown by a reduction in CP amplitude and an increase in CP frequency with the VF. One explanation for the difference in LAT sway modification between healthy elderly and stroke patients may be related to the fact that VF forced stroke patients to become more aware of their weight bearing asymmetry and helped them to become more symmetrical in this respect, as seen in previous studies[9,16]. Such a symmetrization may have led to a tighter sway control in the frontal plane as a result of an increased weight bearing on the paretic limb. Indeed, patients bore 23.6% less weight on their paretic than on their nonparetic leg during the EO task, compared to only 4.5% difference during the VF task, indicating a substantial symmetrization. However, visual analysis on a patient-to-patient basis did not clearly indicate that the degree of symmetrization was associated with the degree of frontal plane stabilization. Both the healthy elderly and the stroke patients demonstrated higher CP amplitudes and velocities than the healthy young participants, particularly in the sagittal plane, suggesting greater postural imbalance. This sagittal plane imbalance may well be related to aging. Many studies have demonstrated that with aging sensory integration deficits become more frequent which may lead to increased postural sway and impaired sway control[6]. Therefore, it is most likely that the elderly and stroke patients were not able to significantly modify their sagittal plane balance with the addition of VF because of sensory integration deficits that are associated with aging. As for frontal plane balance, CP amplitudes and velocities were much higher in the stroke patients than in the healthy elderly and young participants. Hence, results from this study show that LAT sway control seems to provide more specific information regarding the sensorimotor consequences of stroke compared to AP sway control. By applying removal of VF during quiet standing, participants were forced to switch from relying mainly on one sensory (visual) mode to using other sensory modes, while still trying to minimize their body sway. When VF was removed, both the healthy elderly and the stroke patients showed an increase in CP amplitude and a decrease in frequency, in the sagittal plane, even when compared to the EO condition. In contrast, the young healthy participants were still able to maintain a tight control strategy, characterized by a higher CP frequency, although no longer resulting in amplitude reduction. Again, the destabilization observed in the elderly groups may well be related to aging effects. For example, studies on the psychology of aging have shown that, in general, elderly have greater difficulties in shifting from a more focused attention to a broader attention window[20]. Thus, the results of the feedback removal task may have been influenced both by attention switching difficulties as well as by sensory re-weighting problems associated with aging.

Another explanation for these results might be that young participants rely more effectively on a feedforward type of control whereas elderly and stroke participants were unable to use this type of control effectively and perhaps used a feedback control. As stated in Gatev, et al.[2], when precise control of CP is needed one cannot rely on a passive control where changes in position trigger the regulatory response. Therefore, when visual feedback was removed, participants had to use a feedforward control to be able to regulate CP adequately. Also, when considering postural control as including two parallel processes, one being continuous and the other being related to a stimulus-response, we could argue that young participants were able to use the continuous processes effectively whereas the elderly and stroke participants relied more on the stimulus-response processes[2]. The inability of older adults to use the continuous mode could once again be related to motor and sensory modifications associated with aging.

As for the speed of visual-feedback controlled weight shifting, the healthy young were more successful than the healthy elderly, and the elderly more successful than the stroke patients. However, the imprecision measure only differentiated the stroke patients from the healthy young and elderly, who were both equally precise. This pattern of results suggests that both the elderly and stroke patients need more time to process the VF information to make voluntary weight shifts, whereas only the stroke patients suffer from an additional control problem in the frontal plane, leading to increased imprecision. This imprecision seems another aspect of the frontal plane imbalance that is so characteristic for the postural problems after stroke.

The slower weight shifting performance of the two older groups compared to the young group may again be associated with age-related sensory integration deficits. On the other hand, it may be caused by a more generalized (aspecific) slowing down of the central information processing capacity in older adults. Indeed, it has been shown that with aging the central processing time increases by 1.5-2 times leading to prolonged reaction times[7]. This mental slowness may easily be more pronounced in stroke patients than in healthy elderly, explaining the stepwise decline in speed of weight shifting between the groups (see Fig. 4A).

As expected, during the visual removal task all three groups responded with a decrease in the number of successful hits and an increase in the imprecision of weight shifting. However, although the group x task interactions did not reach significance probably as a result of the small sample sizes, figure 4 shows that these effects were more pronounced in the healthy elderly and in the stroke patients. Again, this sensitivity to the sudden need for sensory re-weighting is probably due to the already mentioned age-related sensory integration deficits and attention switching difficulties.

CONCLUSIONS

In summary, sagittal plane imbalance in healthy elderly and stroke patients may be largely due to the effects of aging, whereas frontal plane imbalance is much more specific for the postural problems associated with stroke. Although VF may help stroke patients to better correct their frontal plane asymmetry and imbalance, providing and removing VF during quiet standing seems to test age-related postural deficits to a greater extent than stroke-related impairments. Similarly, slower weight shifting with VF is a more general effect of aging, whereas increased frontal plane imprecision seems more characteristic of the consequences of stroke. Deterioration of weight shifting performance with the removal of VF is also mainly related to aging. From a clinical point of view, these results suggest that using individualized visual CP feedback could be beneficial for evaluating sensory integration as well as re-weighting capacity. It is, however, important to realize that such tasks are probably more sensitive to age-related than to stroke-related impairments, which should be acknowledged when interpreting functional outcomes especially in elderly patients with stroke. As for stroke, both static and dynamic imbalance in the frontal plane seems the most specific postural consequence and may be closely associated to walking inability in relation to weight shifting difficulties.

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SUPPLIERS

[a] Load cells, type LM-100KA, Kyowa Electronic Instruments Company, Limited, Chofu-Higashiguchi Building 2F, 45-6, Fuda 1-chome, Chofu, Tokyo 182, Japan.

[b] RMP DC-amplifier, type MBP 6218, Elan Schaltelemente GmbH, Holzheimer Weg 50, D-4040 Neuss 1, Germany.

7

General Discussion

'Strengths, capabilities and confidence will have to be built again'

(L. Bissell, 2004)[1]

The primary focus of this thesis was to provide insight into the pathophysiological mechanisms underlying standing balance recovery following supratentorial stroke from the perspective that such insight is necessary to improve rehabilitation strategies aimed at functional recovery in these patients. It appeared that standing balance recovery in rehabilitation inpatients with stroke is characterised by only a partial reduction in weight-bearing asymmetry, whereas the tendency to overload the paretic forefoot and lateral foot edge seems to persist, particularly in those patients with a poor initial degree of motor selectivity of the paretic leg. This 'static' asymmetry is consistently increased when attention is distracted by means of a secondary mental task during quiet standing. This dual-task interference does not easily diminish despite rehabilitation. Yet, most rehabilitation inpatients with stroke are able to gradually reduce their postural sway in both planes, in the frontal plane more than in the sagittal plane. The greatest improvement of postural control is found in the frontal plane while quietly standing without vision, indicating a decrease in visual dependency. However, despite improvements in the overall postural stability, a persistent and substantial asymmetry in the kinetic regulation activity between both legs persists. In parallel with an improved control of quiet standing, voluntary weight-shifting capacity improves in terms of speed and precision. The speed of weight shifting is increased by a proportionate reduction in the weight-transfer time toward either leg.

The overall impression is that, although both automatic and voluntary aspects of postural control may improve during the rehabilitation process, these improvements do not coincide with an equally strong symmetrisation process. Instead, several static and dynamic aspects of postural control persist despite intensive rehabilitation aimed at the restoration of functional symmetry. This general finding leads to the conclusion that other mechanisms than improved weight bearing on the paretic leg and improved regulation activity of this leg must underlie standing balance recovery in severely affected patients that need inpatient rehabilitation. This general conclusion is corroborated by another recent study of standing balance recovery[2] as well as by several recent studies of gait recovery in patients admitted for rehabilitation due to the functional consequences of stroke[3-5]. As for the recovery of functional balance skills, this insight warrants future efforts to elucidate which of the proposed mechanisms in the discussion of chapter two are most critical to this recovery in patients with severe stroke. Without repeating all the suggestions made in chapter two, improvement of trunk control may be a very important focus for future cohort studies aimed at the functional recovery from severe stroke. These studies should be directed both at standing and sitting balance in order to be able to include patients as early as possible after stroke onset. Comparison of unilateral (supratentorial) stroke with other types of stroke (bilateral, infratentorial) may be especially relevant to understand the role of the trunk muscles in the recovery of balance after vascular lesions of the brain. Before going into the clinical implications of the most important results from this thesis, some methodological considerations will be discussed first. Suggestions for future research are given throughout both sections.

METHODOLOGICAL CONSIDERATIONS

Selection of the study population It is important to emphasise that the above-mentioned findings and conclusions are based on a population of patients who had been selected for inpatient rehabilitation. This subgroup of survivors from stroke is, no doubt, very relevant with regard to rehabilitation needs and efforts required to reach an independent living situation and a reasonable level of social participation. Most others that have studied the functional recovery of standing balance have included more or less the same subgroup of survivors from stroke, in terms of both age and severity[2,6-8], although country-specific referral policies may have led to somewhat differrent patient characteristics among these studies (e.g. relatively old patients in the study by Laufer et al[8]). The consequence of studying functional recovery from stroke in such a selected study population is that it does not provide insight in standing balance recovery in other subgroups of survivors from stroke, e.g. in those who are less severely affected and, therefore, discharged directly to their homes. It may well be that in this majority of patients (about 50%, see chapter 1) different recovery characteristics might be found, once they would be subjected to similar functional evaluations of balance and gait. Indeed, patients with the best prognosis for motor recovery are probably not selected for admission in a rehabilitation centre in a country where well-developed systems for outpatient rehabilitation and paramedical care are available. Hence, one must be cautious to generalise the above-mentioned conclusions to the majority of stroke survivors, who may well show more signs of resymmetrisation. The results of this thesis have also limited meaning with regard to functional balance recovery in those patients who have survived recurrent strokes. It is likely that this group is characterised by relatively poor 'natural' recovery as well as severe trunk control deficits, especially those patients with bilateral supratentorial strokes. Lastly, patients with infratentorial stroke (e.g. of the brainstem or the cerebellum) are prone to suffer from certain impairments (e.g. ataxia or bilateral paresis) with little possibility of compensation by an 'unaffected' body side. It is likely that such patients will have different recovery potential and use other compensatory strategies than those with a unilateral stroke in one of the cerebral hemispheres.

Start of the posturographic assessments Each quiet-standing and voluntary weight-shifting task had to be recorded without the availability of external forces other than the ground reaction forces. Therefore, the ability to stand unassisted for at least 30 seconds was taken as a functional criterion to start the series of balance assessments. This criterion resulted in a large interindividual variation in the time post stroke onset (TPO) at the start of the assessments (3-24 weeks) and an average TPO of 10 weeks. This relatively long average TPO is indicative of the severity of the sensorimotor deficits in the included patients compared to other studies, which is supported by the frequency of e.g. trunk control deficits at baseline. On the other hand, the ability to stand unassisted was evaluated by various treating physiotherapists who were not directly involved in the study, which may have led to unneccessary hesitations with regard to a patient's ability to participate in the posturographic assessments. As a consequence, it is possible that early recovery characteristics have been missed in some of the more severe patients.

Theoretically, the applied functional criterion for the start of the posturographic assessments may have neutralised the possible influence of some of the clinical characteristics at baseline on standing balance recovery due to their association with the TPO (e.g. the degree of leg motor selectivity). Yet, several other studies of patients with stroke have found surprisingly little effect of sensorimotor deficits on functional balance skills as well[2, 9-11]. The finding that also the TPO itself had no clear influence on balance recovery underscores the notion that a substantial proportion of the potential for balance recovery from stroke is not dependent on the restoration of sensorimotor functions of the paretic leg. Nonetheless, due to the still limited number of included patients, lack of power to identify possible associations cannot be excluded.

Posturography. Force-platform posturography permits the evaluation of static (i.e. related to COP position) and dynamic (i.e. related to COP movement) characteristics of standing balance in both the lateral and the AP directions. This directional distinction is important because posture during normal biped standing is controlled quite differently in either plane of motion[12]. The use of dual plates allows the investigation of static and dynamic characteristics of postural control for each leg separately. This left-right distinction is essential to be able to identify all aspects of

asymmetry. The results of this thesis (chapters 3 and 4) clearly indicate the advantage of this technology compared to single-plate kinetic or kinematic posturography.
The static parameters based on the average COP position (reflecting phenomena such as weight-bearing asymmetry, body inclination, pes equinus and pes varus) are always expressed as a percentage of the length or width of the base of support (see chapter 3), assuming that both feet are in touch with the ground. Because some patients with stroke may suffer from a tendency towards (spastic) equinovarus deviation at the paretic ankle and foot, maximal effort was made to achieve optimal foot contact with the ground during all posturographic assessments. For this reason, the treating physiotherapist sometimes assisted in foot placement and heel loading prior to the registration. Although optically we succeeded in plantigrade foot positioning at the paretic side in all patients with stroke, both forefoot and lateral foot edge loading were found in many patients from a kinetic point of view. This finding indicates that, although the heel may be in touch with the ground, the actual amount of heel loading may still be small, thereby limiting the efficacy of ankle mechanisms for the control of posture and gait at the paretic side. Indeed, particularly in the sagittal plane, the efficacy of the moments of force generated about the ankle joints depends on an optimal contact of both feet with a firm support surface[12,13]. Without such contact, the distribution of vertical ground reaction forces cannot be adequately influenced by lower leg muscle activity to counterbalance the accelerations of body mass. Pes equinovarus is, therefore, one of main reasons for the often large asymmetry in the kinetic regulation activity between the legs in patients with unilateral stroke. Every therapeutic effort must be made to improve heel loading in order to optimise both the weight bearing on and the regulation activity of the paretic leg in these patients (see also clinical implications).

In this thesis, the dynamic characteristics of quiet standing have been analysed traditionally, i.e. using summary statistics (RMS or mean) of a variable (COP amplitude, frequency or velocity) in time. Although there is no well developed theory regarding the determinants of the COP fluctuations during quiet standing, it has been argued that traditional analysis disregards some important dynamic COP characteristics[14,15]. In contrast to the traditional analyses, describing the (presumed) time-independent properties of postural sway, dynamical analyses provide insight into the time-varying structure of the COP fluctuations. From this respect, Collins and De Luca[14] introduced stabilogram diffusion analysis (SDA) as an alternative statistical technique to describe the fractal and time evolutionary properties of the COP fluctuations, whereas Baratto et al.[16] introduced sway density analysis in order to quantify the dynamical (i.e. temporal) stability of postural sway. Both of these dynamical analysis techniques were applied to capture the dynamical structure of the COP and as such infer additional information about the strategies of the postural control system[14,17-19].

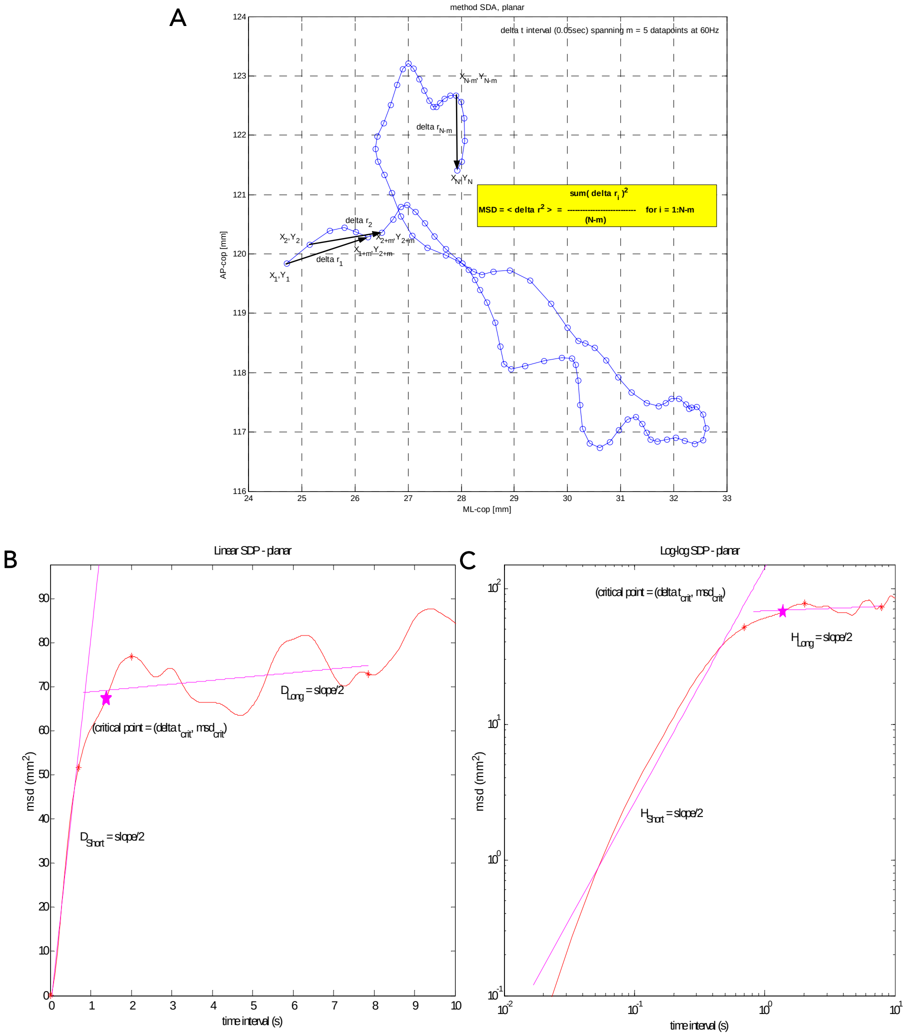
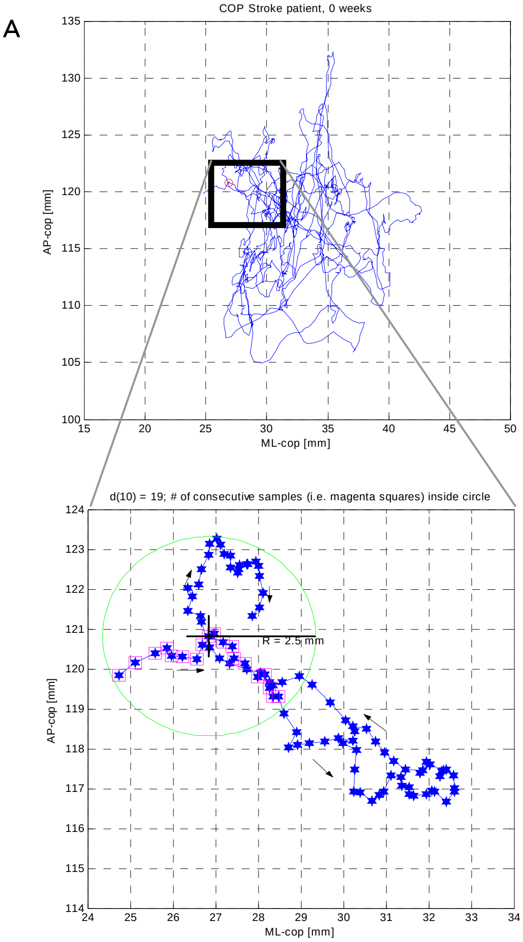


Figure 1. Stabilogram diffusion analysis of an individual registration of a patient with stroke. (A) Calculation of mean squared planar displacement <delta r^2 >. (B) Linear scale plot of mean squared displacement <delta r^2 >. (C) Logarithmic scale plot of mean squared displacement (H>0.5: past and future increments are positively correlated; H<0.5: past and future increments are negatively correlated; H=0.5: classical Brownian motion).

In SDA the displacements between adjacent COP positions separated by a given time interval are squared and averaged. The variance of the displacement increments for time intervals between 0.01 and 10 seconds are displayed (Fig.1). A SDA plot commonly shows two distinct 'linear' regions. These are characterised by two diffusion coefficients and a critical time point. The critical time point divides two regions depicting the short term (open loop) and long term (closed loop) diffusion coefficients (Fig. 1B). The logarithmic scale plot (Fig. 1C) depicts the correlation at different time scales, i.e., the Hurst exponents. Like traditional analysis, SDA has been able to distinguish groups of individuals based on factors such as age [20-22], toe standing[23], the presence of vision[24] or gentle tactile contact[17]. Patients with Parkinson's disease[25] showed disease specific characteristics as well, with increased effective stochastic activity in the mediolateral direction.



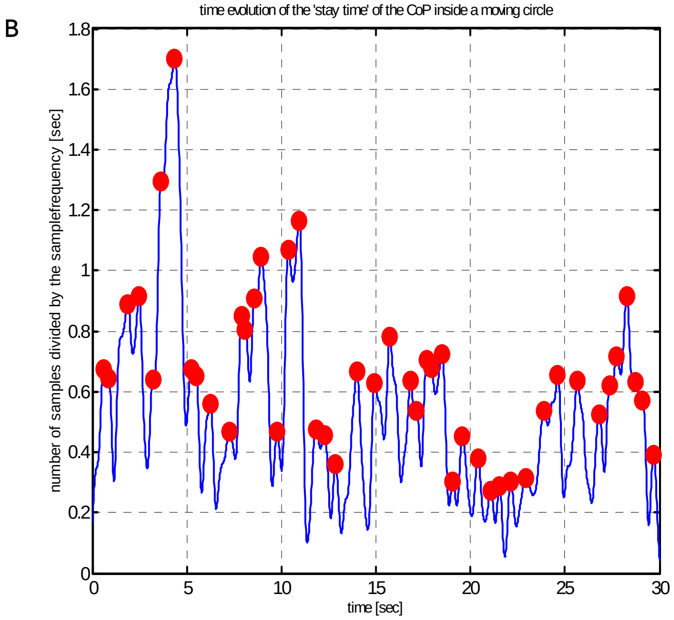


Figure 2. Sway density analysis of an individual registration of a patient with stroke. (A) Calculation of consecutive samples inside a circle centered on a COP position, for each time instant. (B) Peak detection curve: peakes indicate phases of maximal temporary stabilisation.

Sway-density curves (SDC) are graphic constructs that attempt to identify stable points (dense clusters) in the COP evolution by counting, for each COP sample, the number of consecutive COP samples, relative to the sample frequency, falling inside a circle with a given radius (Fig. 2A). Peaks in the SDC, expressed in seconds, correspond to relatively stable time instants in the COP evolution (Fig. 2B). The motivation for this analysis is to identify subunits in the COP data that are thought to be related to the stability of the underlying postural control process. Specifically, Baratto et al.[16] claimed that hidden feedforward control actions or motor commands in the COP signal could be identified by the detection of dense temporal clusters of posturographic samples, interpreted as points in which the feedforward command is most effective. Sway density analysis appears to be sensitive to pathological conditions, indicated by several clinical studies involving (early) Parkinsonian[16,26], diabetic neuropathy[27] and osteoporotic[16] patients.

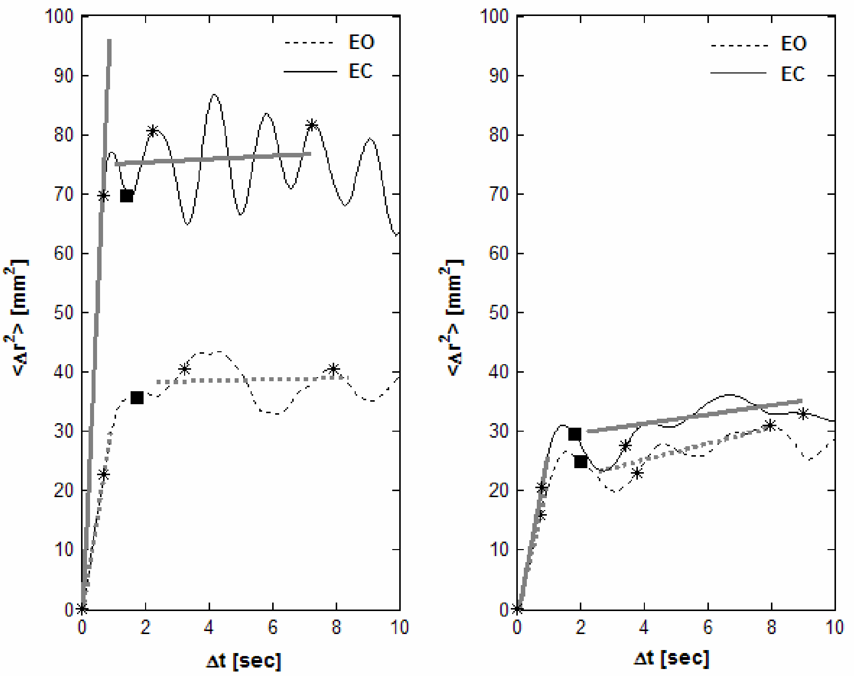


Figure 3. Stabilogram diffusion analysis of an individual patient with stroke before (left) and after (right) rehabilitation. Mean squared planar displacement $<\Delta r^2>$ on linear scales for eyes open (interrupted line) and eyes closed (solid line). Slopes of the linear regression lines through the stabilogram diffusion plots, based on the fit-time coefficients (stars) according to Collins and De Luca (1993)[14], estimate short- and long-term diffusion coefficients. The mean squared displacement at the critical point between the two regions is represented by the solid square. Note that the $<\Delta r^2>$ at the critical point is typically greater for the EC condition than for the EO condition (see Collins and De Luca 1995[28]). In addition, for both conditions the critical point decreased during follow-up.

Although statistical techniques like SDA and SDC are believed to be more sensitive to e.g. age-related differences in postural control than traditional analysis[14,16,29], their advantage in studying postural control and recovery in patients with stroke has yet to be determined. It is, therefore, unclear whether these or any other form of so-called dynamical analysis techniques (e.g. detrended fluctuation analysis[30]) would have yielded different results and conclusions when applied to the data obtained in this study. To this end, the data of the cohort study reported in chapter 3 are currently re-analysed by an independent research group of the Faculty of Human Movement Sciences of the Free University in Amsterdam. In figures 3 and 4 individual data that can be obtained by using SDA and SDC, respectively, are depicted (see figure caption for further details).

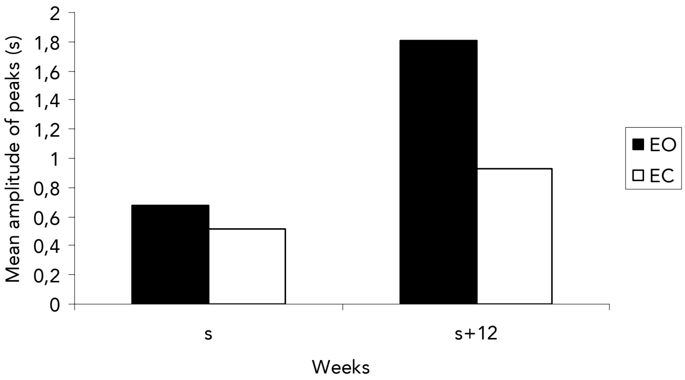


Figure 4. Sway density analysis of an individual patient with stroke before (left) and after (right) rehabilitation. Mean amplitude of the density peaks (in seconds) for the eyes open (EO) and eyes closed (EC) conditions in one stroke patient before and after rehabilitation. Note the difference between conditions with greater stability for the EO condition (longer stay time in the circle for a given radius) and the increase during follow-up, indicative of increase in temporal stability with time. From this perspective, the influence of visual deprivation seems to increase as well.

As for a possible interdependency between static and dynamic COP characteristics, no significant association was found between the average lateral COP deviation from the sagittal midline (as a measure of weight-bearing asymmetry) and any of the dynamic COP measures (see Fig. 5).

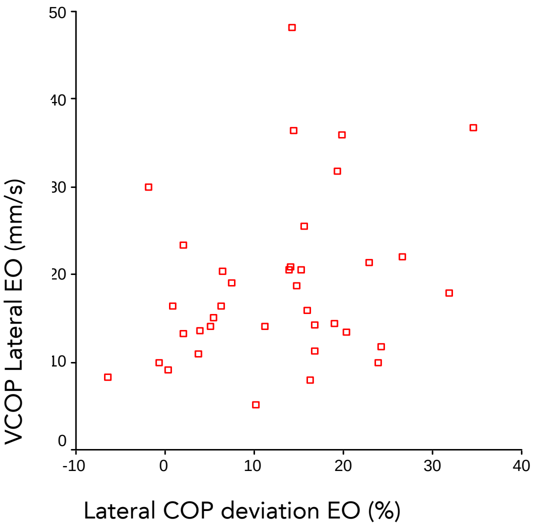


Figure 5. Average lateral COP deviation against the RMS of the lateral COP velocity in the eyes open (EO) condition for all stroke patients (N=37) at the start of the balance training period (r_s = .25).

In contrast, all dynamic COP measures were significantly associated with one another, indicating that no single characteristic of body sway control is fully independent of any other dynamic characteristic, even when comparing quiet standing with voluntary weight shifting (see chapter 4). Apparently, weight-bearing asymmetry cannot explain extra differences in postural instability between patients with stroke. In other words, there are patients who may stand quite asymmetric but relatively stable, whereas others may stand quite symmetric but much less stable. This variety in individual performance is clearly illustrated in figure 5.

This lack of association between weight-bearing and postural stability among different patients by no means defies the possibility that weight-bearing asymmetry and postural instability are interdependent within individual patients. For instance, if quietly standing stroke patients who spontaneously adopt an asymmetric loading pattern would be forced to bear more weight on their paretic or nonparetic leg, they may well become less stable in both instances compared to their preferred asymmetric position. This intra-individual relationship between weight bearing and postural stability, however, has not yet been systematically evaluated. Preliminary results of a study conducted at St. Maartenskliniek Research, Development & Education investigating the effects of various degrees of asymmetric weight distribution on postural stability in healthy elderly and in patients with stroke suggest that such intra-individual interdependency may well be the case. As for stroke, it is particularly relevant whether patients are always able to spontaneoulsy adopt their (individual) optimum of weight distribution. If certain patients would not, one should interpret their postural stability in view of the deviation from their (individual) optimum of weight distribution. Future research should further unravel the intraindividual interdependency of weight distribution and postural stability in patients with stroke.

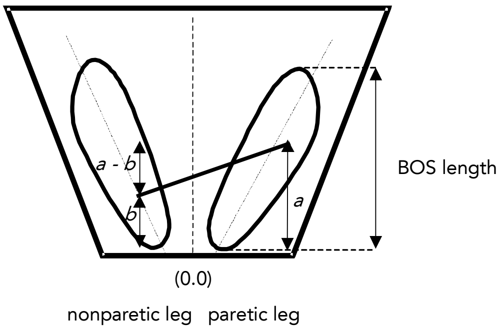
Task conditions In this study posturography was assessed under 4 different conditions: standing with the eyes open, with the eyes closed, while performing a concurrent arithmetic task and while standing facing a vertical midline reference. Standing with eyes open was used as a reference condition to assess the effects of other task conditions. As in many other studies, standing with the eyes closed proved to be very discriminative with regard to postural stability[8,11,31,32]. In contrast, the dual-task condition did not have a profound effect on standing balance. It should be considered, however, that such dual-task interference may have been masked by an aggravating effect of secondary task performance on weight-bearing asymmetry. Because weight-bearing symmetry and postural stability may be interdependent intra-individually, it is possible that a deleterious effect of secondary task performance on postural stability has been obscured by a similar effect on weight-bearing symmetry. On the other hand, the selected secondary task (single-digit summations) was relatively simple in order to be applicable in all patients. This fact may, in turn, have led to a lack of strength to elicit dual-task interference. It would have been of interest to have tested the patients with their eyes closed while simultaneously performing the arithmetic task, however, based on clinical experience, it was expected that too many patients would not have been able to cope with such complex task demands for 30 seconds. In contrast with the other two task manipulations, the condition with a vertical midline reference was used to assess whether weight-bearing asymmetry would be positively influenced by this visual cue, especially in patients with impaired somatosensory feedback or hemineglect[33]. Although there was a tendency towards more symmetry in the presence of a vertical midline reference, the magnitude of this effect was almost negligible. This lack of influence was not due to a possible floor effect, because weight-bearing asymmetry remained substantial throughout the follow-up period. Apparently, providing a simple visual reference of verticality has little impact on the weight-bearing asymmetry caused by stroke-related sensorimotor and cognitive deficits. However, it is still possible that other types of sensory cueing are more effective in restoring weight-bearing symmetry in specific subgroups of patients, which might have implications for determining training strategies for these patients.

Length of follow up The few studies that have dealt with the recovery of standing balance from stroke[6,34-37] have all been restricted to two assessments with a time interval varying from 3 to 16 weeks. To better determine certain recovery profiles, in this study five balance assessments were made at time intervals of 2 or 4 weeks over a total follow-up period of 12 weeks. Some aspects of standing balance recovery appeared to stabilise already after 4 weeks (e.g. weight-bearing symmetry) or 8 weeks (e.g. weight-shifting speed), whereas other aspects of balance (e.g. postural stability, precision of weight-shifting) showed a consistent tendency to improve over the 12-week follow up. In particular, the RMS velocity of the COP fluctuations in both directions of sway during quiet standing gradually decreased without reaching the reference values of healthy elderly. Consequently, further improvement of postural stability might have been found when the follow-up period would have been longer than 12 weeks. It is very unlikely, however, that the control of quiet standing in our cohort would have approached reference values of healthy elderly, considering the postural instability observed in the chronic phase of stroke by many authors[37-40].

CLINICAL IMPLICATIONS

Physical balance training In the second chapter of this thesis it was argued that no firm conclusions can be drawn about the best therapeutic approach to influence the speed or extent of standing balance recovery from stroke. For instance, it was stated that there is little evidence of the efficacy of 'static' or 'dynamic' force-feedback training on either weight-bearing symmetry or postural stability during unperturbed standing. Recently, a Cochrane review of force-platform feedback in patients with stroke has been published that corroborates this conclusion with regard to postural sway parameters and clinical measures of balance[41]. Although this review argues that force-feedback training may improve weight-bearing symmetry, one should be hesitant to support this conclusion. Because stance symmetry was typically assessed using the same equipment as with which patients were trained (and because weight bearing can easily be influenced consciously), the results on which this conclusion was based may have been biased by test-specific learning or by expectation effects. In chapter two, it is concluded that there is preliminary evidence of the efficacy of repetitive sit-to-stand training using biofeedback on dynamic standing balance skills, especially sit-to-stand transfers. This is underscored by a recent systematic review of physical therapy interventions in stroke[42]. This systematic review additionally states that standing balance training using biofeedback may reduce postural sway and improve the symmetry of weight distribution between the paretic and the nonparetic leg, but it does not consider the methodological pitfalls mentioned in chapter 2 of this thesis. It appears, therefore, scientifically sound to still adhere to the more cautious interpretation that no established physical therapy approach, including biofeedback training, has a clear (unbiased) impact on either the symmetry or the control of standing balance following stroke. As for biofeedback, the results reported in chapter six of this thesis also indicate that neither healthy elderly nor stroke patients are readily able to improve their postural stability using visual feedback of centre-of-pressure movements. Recently, a multicentre randomised controlled trial has been conducted to investigate whether intensive somatosensory stimulation (daily sessions of whole body vibration (WBV) during 6 weeks) has a differential effect on sitting or standing balance recovery in the early phase post stroke, since short-term beneficial effects of WBV on force-platform posturographic parameters had been found in the chronic phase of stroke[43]. The interim results of this RCT, however, using the Berg Balance Scale as the primary outcome measure were as yet negative[44]. A few years ago, Johansson and co-workers[45] also withdrew their earlier claim[46,47] that intensive somatosensory stimulation by electroacupuncture can improve the natural balance recovery from stroke.

Apparently, the equilibrium reactions that are evaluated using force-platform posturography during quiet standing can improve as result of neurological or 'natural' recovery (as was shown in chapter 3), but are not easily influenced by specific types of physical training. It is important to consider the clinical implications of this conclusion. On the one hand, it is possible that all the intervention strategies studied in the literature have been inadequate. On the other hand, it may well be that basic equilibrium reactions are neurophysiologically organised at such an automatic level that they are very hard to improve by motor learning. If this latter notion is true, it might mean that the focus of physical therapy should be more directed at those aspects of standing balance control that can be influenced by volition or cognition such as adopting an adequate base of support (BOS) in various situations and making timely adjustments of the BOS by means of multidirectional stepping responses. Indeed, various weight transfers (e.g. sit-to-stance) that require voluntary control seem to be more responsive to targeted training[42]. It should be an important focus for future research to further corroborate this theoretical assumption. Along a different line of thinking one might hypothesise that the restoration of functional balance skills, including basic equilibrium reactions, should be forced by training patients in more complex environmental and task conditions (e.g. during sensory deprivation or manipulation and while performing concurrent mental or motor tasks). There is, indeed, preliminary evidence that balance training during visual deprivation is more effective to improve equilibrium reactions under complex sensory conditions (as assessed by the Equitest) than the same training with full vision[48]. In addition, there is growing evidence that fall prevention programmes that incorporate complex environmental and task requirements (e.g. mechanical disturbances or irregularities, sensory deprivation and dual tasking) may significantly reduce fall incidence and obstacle-avoidance performance during gait in frail elderly[49]. Yet, measures of postural sway were not responsive to this fall prevention training, suggesting again that functional improvements are more easily achieved at a non-automatic level of balance and gait control. Because training programmes that incorporate various complex environmental and task requirements have not yet been evaluated after stroke, it is important that similar studies are conducted in the near future targeted at these patients as well.



A

PCOPAP (%)	Paretic leg (a)	Nonparetic leg (b)	Pes equinus (a-b)
Before BTX-A	58.1	41.5	16.6
After BTX-A	51.4	39.6	11.8

B

PCOPAP (%)	Paretic leg (a)	Nonparetic leg (b)	Pes equinus (a-b)
Barefoot	55.9	36.9	19
Ready made Footwear	49.7	38.6	11.1

Figure 6 . The degree of pes equinus as the difference in average COP position between both feet in relation to the length of the base of support (BOS) before and after BTX-A injection, while standing barefoot (A) and with ready made footwear (B) during the eyes open condition. Pes equinus = a-b / BOS length (N=1).

Chemical and mechanical interventions Instead of focusing solely on the promotion of balance recovery from stroke by physical training of motor functions and postural skills, it is relevant to also explore the effects of a more indirect approach. From a theoretical point of view, it seems relevant to re-establish the mechanical prerequisites for postural control such as sufficient joint mobility and muscle length in both legs for adequate foot contact with the ground and, thus, an optimal base of support. As stated earlier, particularly a pes equinovarus on the paretic side may interfere with the support functions and equilibrium reactions of the paretic leg. The results of chapter three have shown that the problem of pes equinovarus may easily be underestimated in patients who appear to load their foot adequately by achieving physical contact with the ground. Yet, in many of these patients abnormal forefoot and lateral foot edge loading can still be demonstrated by an anteriorly and laterally displaced average COP position.

Since the equinus and varus tendency on the paretic side in stance is initially caused by neurogenic hypertonic activity of the posterior lower leg muscles, the use of botulinum toxin type A (BTX-A) injections into these muscles may be a logical strategy to reduce this hypertonia and, thereby, improve heel loading, weight bearing and standing balance. A pilot study[50] has provided some evidence in favour of this strategy in individual patients with stroke (see Fig. 6a for a single case report). However, loss of passive muscle compliance and muscle length was a complicating factor to achieve consistent results among patients. Furthermore, in some patients improved heel loading did not coincide with improved postural stability, perhaps because the concomitant reduction in lower leg muscle strength was a negative side effect. The use of BTX-A to improve foot loading in patients with stroke is nevertheless an interesting direction for future research in this area. When foot loading cannot be optimised by BTX-A injections in the posterior muscles of the lower leg due to muscle stiffness or contracture, intervention strategies aimed at muscle lengthening may be beneficial. One might think of stretching exercises, (night time) splinting or, ultimately, surgical muscle tendon lengthening.

The evidence of all such measures for improving standing balance needs to be provided by future research. Another strategy to improve heel loading and weight bearing after stroke is the use of individually tailored ankle-foot orthoses (AFOs) or footwear to compensate for the loss of mobility or deformation at the ankle joint. Already in chapter 2 the significant influence of shoe adaptations on loading characteristics in patients with stroke has been reviewed. Also in this area, we recently conducted a pilot study. The general impression of these preliminary evaluations was that even normal, ready-made footwear can normalise the loading pattern on the paretic side in patients with stroke (see Fig. 6b for a single case report). Simply by raising the heel approximately 2 cm and providing good support to the whole plantar area of the foot, the average COP may displace posteriorly to a more normal position. The additional effects of AFOs or orthopaedic footwear appeared to be rather limited and inconsistent in this respect.

Again, improved foot loading did not always coincide with better postural stability, but it certainly seems warranted to further elaborate on this topic in future research. Lastly, as was also mentioned in chapter two, the effects of (walking) aids on loading characteristics and balance appear to be relatively large. Given the scarcity of scientific, comparative studies in this field, much more research effort directed at the influence of aids on functional balance skills seems justified.

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Summary

A majority of the survivors from stroke suffer from a combination of sensory, motor and cognitive impairments. As a consequence, postural control is often impaired which is reflected in balance problems while standing and walking. The importance of a sound efferent and afferent control of posture while standing is given in chapter 1. It is emphasised that maintaining standing balance is not a passive activity but dependent on subtle equilibrium reactions generated by leg and trunk muscles and controlled by different senses that maintain the body's centre of mass over a fixed base of support. Maintaining standing balance is based on the information provided by the visual, somatosensory and vestibular systems. If this information is disturbed, a shift in the 'weight' of the different senses may occur. Consequently, balance problems may easily be masked if no sensory manipulations would be used in clinical assessments. Similarly, dual-task conditions should be used to assess the attention demands of standing. Because one of the main goals in the rehabilitation of patients with stroke is to have them perform basic activities of daily living independently, interventions to improve the speed and extent of standing balance recovery are needed. To be able to improve stroke rehabilitation, it is essential to have optimal understanding of the potential mechanisms underlying 'natural' balance recovery from stroke. Against this background 5 main research questions focused at (supratentorial) stroke were posed in chapter 1 and elaborated in the following chapters.

In chapter 2 the literature about the mechanical and physiological mechanisms underlying balance recovery from stroke is reviewed. This review is subdivided in sections about unperturbed stance, stance perturbations, voluntary weight displacements and the sensory and cognitive control of posture. During unperturbed stance, weight-bearing asymmetry in favour of the nonparetic leg as well as increased spontaneous postural sway, appear to be characteristic for patients with an incompletely recovered hemiparesis. Relatively small improvements have been found in spontaneous sway reduction and weight-bearing symmetry during rehabilitation. The evidence of force-feedback training on weight-bearing symmetry and stance stability seems rather weak, whereas aids such as shoe adaptations, ankle-foot orthoses and canes may considerably improve weight-bearing symmetry. The use of canes may also improve stance stability. While standing, internal (self-initiated) and external perturbations are a continuous threat to the maintenance of balance. Patients with stroke choose certain 'stabilisation' strategies, i.e. they allow less passive body mass displacement as well as self-initiated movement. Compensatory muscle activation on the nonparetic side is an important mechanism for maintaining postural stability during both unperturbed and perturbed stance, but does not necessarily prevent recovery of more symmetric and physiological muscle patterns at a later stage in rehabilitation. In patients with stroke, the capacity to make voluntary weight displacements, a prerequisite for safe mobility, appears disturbed as well. Not only is maximal weight shifting impaired, in particular towards the paretic leg, weight shifts are also performed at a slow speed and with poor precision. Transition from bipedal to single-limb stance is impaired due to insufficient hip muscle recruitment on the paretic side and failure to maintain single-limb support on either leg. Compensation of the non-paretic hip muscles as well as recovery of hip muscle function at the paretic side both contribute to the control and recovery of weight-shifting capacity. There is preliminary evidence that biofeedback training may promote dynamic balance skills, especially the speed and symmetry of sit-to-stand transfers. As for the sensory control of posture, patients with stroke may exhibit an excessive reliance on vision. Various explanations have been posed including difficulty of integrating somatosensory information, an inability to select the pertinent sensory input or a nonspecific strategy to compensate for the loss of other sensory input. A clear relationship between the severity of somatosensory impairment and the degree of visual dependence for postural control has not yet been reported. In patients with stroke, the cognitive control of posture may be aggravated as well, which is reflected in increased attention demands for standing. Overall, the influence of motor stage, muscle strength or spasticity of the paretic leg muscles on (the recovery of) static or dynamic standing balance appears less obvious than one would intuitively expect. This finding emphasises the role of other restorative mechanisms. In this perspective, there is a clear lack of knowledge regarding the role of trunk muscles, stepping responses as well as sensory and cognitive reorganisation in (the recovery of) standing balance control following stroke.

In chapters 3, 4 and 5 a cohort of 37 severely affected rehabilitation inpatients with a first supratentorial stroke was assessed over a period of 12 weeks from the moment they could stand unassisted for 30 seconds as well as 2, 4, 8, and 12 weeks later. The first and last assessments were accompanied by a clinical evaluation rating the dependence level of walking using the Functional Ambulation Categories (FAC, 0-5) and a standardised physical and neuropsychological examination. The physical examination provided data for lower-limb motor selectivity according to Brunnstrom (stages I-VI), lower-limb sensation by testing position sense at the ankle (normal or disturbed), lower-limb reflex activity by imposing a fast dorsiflexion at the ankle (clonus absent or present), and trunk control by testing sitting balance on the edge of a bed (normal or disturbed). Visuospatial hemineglect was considered to be present when abnormal lateralisation was found in 2 out of 3 selected visuospatial tests. Posturography assessments consisted of 2 consecutive test series with 4 quiet-standing tasks (with and without a visual midline reference, with the eyes closed and while performing a concurrent arithmetic task) and 1 weight-shifting task (requiring quasi-rhythmic submaximal lateral weight shifts between 2 square targets using visual feedback of the centre of pressure (COP)). Dual-plate force-platform registrations permitted evaluation of static (related to COP position) and dynamic (related to COP movement) characteristics at both sides of the body. For the cohort as a whole, considerable functional gains were found during the follow-up period. The median FAC score improved from 2 (range 1-4) to 4 (range 1-5). In chapters 3 and 4, the posturographic performances of the patients with stroke are compared to those of healthy elderly using the same postural tasks, conditions and parameters.

Chapter 3 focuses on the static aspects of quiet standing balance that improve during functional recovery from stroke. The posturographic results indicate that patients' postural stability substantially increased in both planes in all conditions, most prominently in the frontal plane while standing with the eyes closed. This finding suggests that patients were gradually able to rely more on their somatosensory feedback. Despite improvements in overall postural stability, the patients as a group did not reach reference values obtained from healthy elderly and showed a persistent and substantial asymmetry in the kinetic regulation activity between the legs in all conditions, with approximately twice as high COP velocities on the nonparetic side. Although overloading of the nonparetic leg significantly decreased during the first 4 weeks, a substantial degree of weight-bearing asymmetry persisted as well, especially in patients with disturbed sensibility or ankle clonus. Throughout the follow-up period, attention distraction by concurrent task performance aggravated weight-bearing asymmetry. Despite a significant reduction in weight-bearing asymmetry, the patients as a group showed a persistent and substantial degree of paretic forefoot and lateral foot edge overloading ('pes equinovarus'), particularly the patients with poor motor selectivity. Again, dual-task performance accentuated these static abnormalities. Based on the overall pattern of results, it was concluded that other mechanism than the restoration of support functions and equilibrium reactions exerted through the paretic leg must, at least partially, account for the improvements in postural stability and functional independence during rehabilitation.

Chapter 4 deals with the question how the capacity to voluntarily displace weight recovers during rehabilitation and to what extent this voluntary control of posture is associated with the control of quiet standing. As a group, the patients with stroke were able to improve their ability to make lateral voluntary weight shifts to the nonparetic as well as to the paretic leg. This improvement was reflected in an increased speed (number of weight shifts) and precision (the COP trajectory travelled per weight shift), with precision reaching normal reference values. Generally, it took more time for patients to make a weight shift towards the paretic side than towards the nonparetic side. Nevertheless, weight-shifting speed improved proportionally in both directions. Elderly patients and those with hemineglect were generally slower than younger patients and those with normal perception, but all patients showed a comparable improvement across time. During weight shifting, all patients spent a longer time outside the target area (the area within and in between the 2 targets) than healthy elderly. When outside the target area, all subjects deviated mainly in the anterior direction, showing increased body inclination. Significant and substantial associations were found between weight-shifting (speed and precision) and quiet standing (stability in the frontal and sagittal plane) at the end of the follow-up period. These associations imply that the control of both tasks relies, at least partly, on common physiological mechanisms. On the other hand, the shared variances between the selected parameters are low enough to conclude that the assessment of voluntary weight-shifting capacity significantly adds information about balance performance, compared to the assessment of quiet-standing tasks alone.

In chapter 5 the posturographic outcomes of quiet standing balance and voluntary weight shifting were related to the dependence level of walking. Across all patients and assessments, lateral postural instability in quiet stance, either with eyes open, with a visual vertical midline reference or with the eyes closed, was negatively associated with the FAC score, each condition explaining 37% of the variance in the FAC score. The degree of weight-bearing asymmetry was found negatively associated with the FAC score as well, explaining 35% of its variance, however only during the eyes closed condition. Of the weight-shifting parameters, only the speed of weight transfers was associated with the independence of walking, explaining 32% of its variance. Of all the selected posturographic parameters, those reflecting lateral postural stability in stance showed the strongest association with the FAC score. It was concluded that balance training, as a prerequisite for independent walking, should specifically focus on these lateral aspects of postural control after supratentorial stroke.

In chapter 6 15 healthy young, 15 healthy elderly and 10 patients with chronic stroke were compared for their capacity to use visual COP feedback to control quiet standing and weight shifting. In addition, COP feedback was withdrawn to examine whether subjects could maintain a selected postural strategy without such feedback. Postural control was assessed while standing quietly on a force platform and while voluntarily shifting weight in the frontal plane. Only the healthy young were able to use the visual feedback during quiet standing by decreasing their COP amplitude and increasing their frequency of control in either plane, keeping their COP velocity more or less constant. In contrast, the healthy elderly were unable to adopt such a strategy, whereas the stroke patients were able to reduce their COP amplitude only in the frontal plane. Withdrawal of visual feedback resulted in a 'destabilising' effect in the sagittal plane in both the healthy elderly and the stroke patients. The healthy young were generally more successful at weight shifting in terms of speed and precision compared with healthy elderly, and healthy elderly were more successful than stroke patients. Withdrawal of visual feedback showed that only the young were able to largely maintain their weight-shifting control in the frontal plane. It was concluded that providing or removing visual COP feedback during quiet standing or removing visual feedback during visually controlled weight shifting can discriminate healthy young from healthy elderly, but does not clearly discriminate healthy elderly from stroke patients in the same age group. In addition, the pattern of results suggested that sagittal plane imbalance in healthy elderly and stroke patients may be largely due to the effects of aging, whereas frontal plane imbalance may be more specific for the postural problems associated with stroke.

In the last chapter, chapter 7, the emphasis is laid on the possibilities and limitations of the applied methods, the possible therapeutical implications and directions for future research in both respects. It is acknowledged that the findings and conclusions of this thesis are based on a sample of patients with a first supratentorial stroke that has been selected for inpatient rehabilitation. Hence, the results of this thesis cannot be applied to less severe patients with stroke or to patients with other types of stroke. It is emphasised that the use of a dual-plate force platform allows the investigation of static and dynamic characteristics of postural control for both legs together as well as for each leg separately, leading to specific knowledge of the mechanisms underlying standing balance recovery in lateralised disorders. In this thesis, traditional posturographic parameters have been used to draw conclusions about postural control and symmetry. It is recognised that alternative statistical techniques such as stabilogram diffusion analysis and sway-density curves may be more informative and sensitive than traditional analyses. On the other hand, their advantage in studying postural control and recovery in patients with stroke has yet to be determined. It is suggested that future research should be directed towards the neglected aspects of standing balance recovery mentioned in chapter 2. In addition, the effects of interventions that may optimise the mechanical constraints for maintaining standing balance should be investigated, such as muscle injections with botulinum toxin, the application of ankle-foot orthoses or the use of individualised footwear.

Samenvatting

Door een combinatie van sensibele, motorische en cognitieve stoornissen is bij het merendeel van de CVA patiënten de houdingsregulatie gestoord. Hierdoor kunnen balansproblemen ontstaan die activiteiten zoals staan en lopen kunnen beperken. Het belang van intacte afferente en efferente systemen in de houdingsregulatie wordt in hoofdstuk 1 besproken. In dit hoofdstuk wordt de nadruk gelegd op het feit dat het handhaven van stabalans geen passieve activiteit is, maar afhankelijk van subtiele evenwichtsreakties. Door krachten gegenereerd door been- en rompspieren is het lichaam in staat om het zwaartepunt boven het steunvlak gehouden. Daarbij is het afhankelijk van informatie van het visuele, somatosensore en vestibulaire systeem. Indien de informatie afkomstig van één van deze systemen gestoord is, zal meer gewicht worden toegekend aan de andere systemen. Zo kan het voorkomen dat, indien er geen manipulaties worden toegepast om sensore of cognitieve afhankelijkheid te beoordelen, zoals het opleggen van visuele deprivatie of van een dubbeltaak tijdens staan, er balansproblemen worden gemaskeerd en niet worden herkend. Het zelfstandig uitoefenen van de basisactiviteiten van het dagelijkse leven is een van de hoofddoelen binnen de revalidatie van CVA patiënten. Interventies beogen de snelheid en de mate van stabalansherstel te bevorderen. Hiervoor is kennis van potentiële mechanismen die ten grondslag liggen aan het ´natuurlijke´ beloop essentieel. Tegen deze achtergrond werden 5 onderzoeksvragen, gericht op CVA patiënten met een supratentoriele laesie, geformuleerd en uitgewerkt in de volgende hoofdstukken.

In hoofdstuk 2 wordt een overzicht gegeven van de literatuur betreffende de mechanische en fysiologische mechanismen ten grondslag liggend aan het herstel van stabalans na een CVA. Het review is onderverdeeld in staan met en zonder opgelegde verstoringen en staan tijdens actieve gewichtsverplaatsing, waarna de invloed van de sensore systemen en cognitie op de regulatie van houding wordt besproken. Karakteristiek voor patiënten met een incompleet herstelde hemiparese tijdens staan zonder opgelegde verstoringen zijn een toegenomen posturale zwaai en een asymmetrische gewichtsbelasting van de benen, met meer gewichtsname op het niet-paretische been. Tijdens revalidatie treedt zowel een vermindering van de posturale zwaai op als een toegenomen symmetrie in gewichtsbelasting. Het effect van drukfeedback-training op de symmetrie van gewichtsbelasting en op stabalans is zwak, in tegenstelling tot het effect op gewichtsname symmetrie van voorzieningen zoals schoenaanpassingen, enkel-voet orthesen en krukken. Krukken kunnen ook de posturale zwaai verminderen. Tijdens staan vormen zowel interne (zelf-opgelegde) als externe verstoringen een continue bedreiging voor de handhaving van balans. CVA- patiënten laten daarbij relatief kleine passieve en actieve verplaatsingen van het lichaamszwaartepunt toe. Zij hanteren een zogeheten ´stabilisatie´ strategie. Om balans te handhaven tijdens staan met en zonder verstoringen vindt er een toegenomen, compensatoire, activiteit van de spieren aan de niet-paretische lichaamszijde plaats zonder dat dit het herstel van symmetrische en fysiologische spieractivatiepatronen in een later stadium van de revalidatie belemmert. Een voorwaarde voor een veilige loopvaardigheid is het actief kunnen verplaatsen van het gewicht over beide benen. CVA-patiënten laten tijdens het actief verplaatsen van het gewicht niet alleen een minder grote maximale verplaatsing zien, met name richting het paretische been, maar ook zijn de snelheid en precisie waarmee de verplaatsingen worden uitgevoerd minder. Daarnaast hebben CVA-patiënten ten gevolge van insufficiënte spieractiviteit in de heupspieren aan de paretische zijde problemen om vanuit een positie waarbij beide benen worden belast te komen tot een positie waarbij slechts één been wordt belast. Zowel compensatie van de niet-paretische heupspieren als het herstel van de paretische heupspieren dragen bij aan het herstel van actieve gewichtsverplaatsing. Er is bewijs dat biofeedbacktraining de snelheid en symmetrie van de zit-tot-stand transfer kan bevorderen, echter vooralsnog berust dit bewijs op preliminaire data. Voor wat betreft de sensore regulatie van de houding is het bekend dat CVA patiënten een grotere visuele afhankelijkheid tonen. Hiervoor worden verschillende verklaringen gegeven zoals moeizame integratie van somatosensore informatie, onvermogen om de meest relevante sensore input te selecteren en uiting van een aspecifieke strategie om te compenseren voor de gestoorde somatosensoriek. Een duidelijke relatie tussen de ernst van de somatosensore stoornis en de mate van visuele afhankelijkheid voor de houdingsregulatie is tot op heden echter niet aangetoond. Naast verhoogde visuele afhankelijkheid kan er ook sprake zijn van een verhoogde cognitieve regulatie, hetgeen tot uiting komt in een toegenomen behoefte aan aandacht tijdens het staan. De invloed van de ernst van motorische problemen van de paretische beenspieren op (het herstel van) statische en dynamische stabalans blijkt minder uitgesproken te zijn dan men zou verwachten. Deze bevinding benadrukt de rol van andere herstelmechanismen dan het herstel van motoriek, kracht of vermindering van spasticiteit. Onduidelijk in dit geheel blijft vooralsnog de invloed van de rompspieren, de betekenis van stapreacties en de rol van sensore en cognitieve reorganisatie.

Het onderzoekscohort van hoofdstukken 3, 4 en 5 bestaat uit 37 ernstig aangedane CVA patienten met een supratentoriele laesie, gemeten tijdens hun klinische opname in een revalidatiecentrum, vanaf het moment dat zij zonder hulp 30 seconden konden staan en 2, 4, 8 en 12 weken later. Tijdens de eerste en laatste meting werd het afhankelijkheidsnivo van lopen met behulp van de 'Functional Ambulation Categories' (FAC, 0-5) bepaald. Bij de eerste meting werd tevens een gestandaardiseerd lichamelijk en neuropsychologisch onderzoek verricht. Het lichamelijk onderzoek bestond uit een beoordeling van de selectiviteit van het paretische been (Brunnstrom stagering (I-VI)), de positiezin van de enkel (normaal of gestoord), de reflexactiviteit door middel van een snelle passieve dorsaalflexie van de enkel (clonus aanwezig of afwezig), en de rompbalans door middel van een beoordeling van de mate van zitbalans op de rand van het bed (normaal of gestoord). De aanwezigheid van een visuospatieel hemineglect werd gebaseerd op een abnormale lateralisatie tijdens 2 van de 3 geselecteerde visuospatiele testen. De posturografische metingen bestonden uit 2 test reeksen met elk 4 rustige stabalanstaken (staan met en zonder een verticale middenlijn referentie, met de ogen dicht en tijdens het gelijktijdig uitvoeren van een rekentaak) en 1 actieve gewichtverplaatsingstaak. Voor de gewichtverplaatsingstaak kreeg de patient de opdracht om zo snel en zo vloeiend mogelijk een submaximale laterale gewichtsverplaatsing uit te voeren. Hierbij maakten zij gebruik van visuele feedback van het aangrijpingspunt van de grondreactiekrachten (Center of Pressure, COP). De submaximale laterale gewichtverplaatsingen werden op een computerscherm gevisualiseerd en tevens twee vierkante doelen. Door registraties met een krachtenplatform dat uit twee gescheiden platen bestaat, is het mogelijk om een indruk te krijgen van de statische (gerelateerd aan de COP positie) en dynamische (gerelateerd aan de COP bewegingen) karakteristieken aan beide zijden van het lichaam. Het gehele onderzoekscohort ging qua vaardigheden vooruit. Gedurende de follow-up periode verbeterde de mediane FAC-score van 2 (range 1-4) naar 4 (range 1-5). In hoofdstukken 3 en 4 worden de krachtenplatformresultaten van het onderzoekscohort vergeleken met de prestaties van gezonde ouderen, gemeten met hetzelfde krachtenplatform, gebruik makend van dezelfde taken, condities en parameters.

In hoofdstuk 3 worden de statische aspecten van het staan onderzocht. Op basis van de uitkomsten van metingen met het krachtenplatform blijkt de stabiliteit tijdens staan substantieel te verbeteren in zowel voor-achterwaartse als laterale richting onder alle condities, maar het meest uitgesproken in de laterale richting tijdens het staan met ogen dicht. Deze laatste bevinding wijst op een geleidelijke toename van het gebruik van somatosensore input. Ondanks de toename in stabiliteit worden aan het einde van de follow-up periode de normaalwaarden van gezonde ouderen niet bereikt en blijft er in alle condities een substantiële asymmetrie in de kinetische regulatieaktiviteit van de benen bestaan met gemiddeld twee maal zo grote COP snelheden onder het niet-paretische been. Ook voor de asymmetrische gewichtsbelasting blijft er, alhoewel er de eerste 4 weken een significante verbetering plaatsvond, een substantiele asymmetrie bestaan, vooral bij patiënten met een gestoorde sensibiliteit en een aanwezige enkelclonus. Het gelijktijdig uitvoeren van een rekentaak leidde tijdens de gehele follow-up tot toegenomen asymmetrische gewichtsbelasting. Het onderzoekscohort in zijn geheel, maar vooral de groep patiënten met een beperkte motorische selectiviteit, behield gedurende de follow-up periode een versterkte voorvoet- en laterale voetrandbelasting ('pes equinovarus'), ondanks de significante vermindering in de totale asymmetrische gewichtsbelasting. Ook deze belastingsparameters bleken meer af te wijken tijdens het uitvoeren van een dubbeltaak. Op basis van de gevonden resultaten is het waarschijnlijk dat andere mechanismen dan alleen het herstel van steunfuncties en evenwichtsreakties van het paretische been een rol spelen bij het herstel van posturale stabiliteit en de toename van functionele onafhankelijkheid gedurende de revalidatie.

Hoofdstuk 4 behandelt de vraag in hoeverre CVA patiënten tijdens hun revalidatie beter in staat zijn om actief het gewicht te verplaatsen en hoe deze actieve gewichtverplaatsing is gerelateerd aan de regulatie van het rustig stil staan. Het onderzoekscohort liet een toegenomen snelheid (aantal gewichtverplaatsingen in 30 seconden) en precisie (COP traject per gewichtverplaatsing) zien, waarbij de laatste parameter zelfs de normaalwaarden van gezonde ouderen bereikte. Ondanks het gegeven dat de CVA patienten meer tijd nodig hadden om het gewicht van het niet-paretische been naar het paretische been te verplaatsen, verbeterde de snelheid relatief even sterk in beide richtingen. Alle patiënten toonden een vergelijkbare verbetering in de tijd, alleen de oudere CVA patient ($\geq$ 65 jaar) en degenen met een hemineglect verplaatsten hun gewicht over het algemeen langzamer dan jongere patiënten (<65 jaar) en degenen bij wie geen hemineglect was vastgesteld. Tijdens het actief gewichtverplaatsen beweegt het COP zich idealiter in het gebied van en tussen de twee vierkante doelen. Ten opzichte van gezonde ouderen bewoog het COP van CVA patiënten zich vaker buiten dit doelgebied, veelal anterieur, hetgeen duidt op een voorwaartse verplaatsing van het lichaam. De relatie tussen actieve gewichtverplaatsing (snelheid en precisie) en rustig stil staan zonder opgelegde verstoringen (stabiliteit in de antero-posterieure en laterale richting) was aan het einde van de follow-up periode significant en substantieel. De grootte van de associaties impliceert dat de regulatie van beide taken, in ieder geval gedeeltelijk, op gemeenschappelijke fysiologische mechanismen berust. Tegelijkertijd zijn de associaties niet zo groot dat er geen toegevoegde waarde van de uitkomsten van de posturografische parameters tijdens actieve gewichtverplaatsingstaak verwacht mag worden om een indruk te krijgen van de balanshandhaving.

De uitkomstmaten van zowel het rustig stil staan als het actief gewicht verplaatsen werden in hoofdstuk 5 gerelateerd aan het nivo van afhankelijkheid tijdens lopen. De verklaarde variantie in de FAC score door posturale stabiliteit in de zijwaarste richting tijdens het stil staan was 37% voor zowel staan met ogen open, met een visuele middenlijn als met de ogen gesloten. De verklaarde variantie in de FAC score door asymmetrische gewichtsbelasting was 35% tijdens stil staan met de ogen dicht. Voor beide parameters was er sprake van een negatieve associatie met de FAC score. Van de actieve gewichtverplaatsingstaak bleek alleen de snelheid geassocieerd te zijn met de onafhankelijkheid van het lopen met een verklaarde variantie van 32%. Van alle geselecteerde posturografische parameters bleken de parameters in de laterale richting het sterkst geassocieerd te zijn met de FAC score. Balans training zou dan ook speciaal gericht moeten zijn op de laterale aspecten van de houdingsregulatie na een CVA.

In hoofdstuk 6 werd de capaciteit om visuele COP feedback te gebruiken om stabalans te reguleren en om actief gewicht te verplaatsen vergeleken tussen 15 gezonde jongeren, 15 gezonde ouderen en 10 CVA patiënten. Ook werd beoordeeld of de geleverde prestatie tijdens visuele COP feedback vastgehouden kon worden wanneer de feedback onttrokken werd. Alleen de gezonde jongeren waren in staat om met visuele feedback hun COP amplitude te verminderen en de COP frequentie te vergroten in beide richtingen, waarbij ze in staat waren min of meer dezelfde COP snelheid te houden. De gezonde ouderen, daarentegen, waren niet in staat tot een dergelijke verandering van strategie. De CVA patiënten waren wel in staat hun COP amplitude te verminderen, echter alleen in de laterale richting. Het onttrekken van de COP feedback aan het visuele veld leidde tot een 'destabiliserend' effect in de voor-achterwaartse richting bij zowel de gezonde ouderen als de CVA patiënten. In het algemeen waren de gezonde jongeren meer succesvol (snelheid en precisie) in het actief gewicht verplaatsen dan gezonde ouderen, en waren gezonde ouderen meer succesvol dan CVA patiënten. Indien de COP feedback werd onttrokken tijdens het actief gewicht verplaatsen bleken alleen de jongeren in staat om nog succesvol alternerend van doel tot doel te bewegen. Het hoofdstuk eindigt met de conclusie dat het aanbieden en onttrekken van visuele COP feedback tijdens staan zonder verstoringen en het onttrekken van visuele COP feedback tijdens actieve gewichtsverplaatsing wel discrimineert tussen gezonde jongeren en gezonde ouderen, maar niet duidelijk tussen gezonde ouderen en CVA patiënten van dezelfde leeftijd. De gevonden voor-achterwaartse instabiliteit bij gezonde ouderen en CVA patiënten lijkt daarbij vooral samen te hangen met de leeftijd, terwijl de laterale instabiliteit meer specifiek lijkt voor de gevolgen van een CVA.

In het laatste hoofdstuk, hoofdstuk 7, wordt de nadruk gelegd op de mogelijkheden en beperkingen van de gebruikte methoden in het onderzoek. Er wordt ingegaan op enkele therapeutische implicaties en er worden suggesties gedaan voor verder onderzoek. Er wordt benadrukt dat de onderzoeksresultaten betrekking hebben op een geselecteerde groep CVA patienten met een eerste supratentoriele laesie die opgenomen zijn voor een klinische revalidatiebehandeling. Ze zijn daardoor niet van toepassing zijn op minder ernstig aangedane CVA patiënten. De voordelen van het gebruik van een krachtenplatform bestaande uit twee gescheiden platen worden onderstreept. Een dergelijk krachtenplatform maakt het mogelijk om statische en dynamische karakteristieken van houdingsregulatie te meten van beide benen tegelijk als ook van elk been apart. Dit geeft de mogelijkheid om inzicht te krijgen in het herstel van stabalans bij gelateraliseerde aandoeningen. De conclusies met betrekking tot houdingsregulatie en -symmetrie worden in dit proefschrift getrokken op basis van zogenoemde 'traditionele' parameters. Alternatieve statistische technieken zoals 'stabilogram diffusion analysis' en het gebruik van 'sway-density curves' worden besproken. Mogelijk bevatten deze laatste methoden meer informatie en zouden ze sensitiever kunnen zijn dan de gebruikte traditionele parameters. Tot op heden zijn deze analyse methoden echter nog niet toegepast op krachtenplatformdata van CVA patiënten. Suggesties voor vervolgonderzoek worden gegeven waarbij wordt teruggegrepen op de verschillende hiaten in de kennis van het herstel van stabalans na CVA, zoals genoemd in hoofdstuk 2. Er worden suggesties geformuleerd voor interventiestudies naar de effecten van botulinetoxine injecties, enkel-voet orthesen en het gebruik van orthopedisch maatschoeisel op stabalans.

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Curriculum Vitae and List of Publications

CURRICULUM VITAE

Mirjam de Haart werd op 2 maart 1968 geboren te Maassluis. In 1987 behaalde zij het VWO examen aan het Chr. Scholengemeenschap 'Comenius' te Capelle aan den IJssel. In het studiejaar 1987 – 1988 behaalde zij haar propaedeutisch diploma voor de studie Gezondheidswetenschappen aan de Rijksuniversiteit Limburg te Maastricht. In de studiejaren 1988 – 1992 volgde zij het doctoraalprogramma van de studie Geneeskunde, eveneens aan de Rijksuniversiteit Limburg te Maastricht. Haar wetenschappelijke stage op de afdeling radiologie van het Academisch Ziekenhuis Maastricht leidde tot haar eerste wetenschappelijke publicatie. Om inzicht te krijgen in de biomechanica volgde zij in het studiejaar 1992 – 1993 de theoretische vakken van de studie Werktuigbouwkunde aan de Technische Universiteit van Eindhoven en voldeed zij voor deze vakken aan de eisen van het propaedeutisch diploma. In hetzelfde jaar verrichtte zij een Werktuigbouwkundige stageopdracht naar de bepaling van validiteit en betrouwbaarheid van een bewegingsopnemer voor het registreren van lichaamsbewegingen, onder leiding van drs. C.V.C. Bouten. Van 1993 – 1995 liep zij haar co-schappen en behaalde zij haar artsexamen. Naast haar co-schappen participeerde zij in een onderzoek naar de gangbeeldanalyse voor en na implantatie van totale knieprothesen in honden, uitgevoerd door drs. D. Dartee, afdeling Orthopaedie, Academisch Ziekenhuis Maastricht. Aansluitend aan het arts-examen heeft zij 3 maanden als AGNIO gewerkt op de afdeling Orthopaedie van het Maasland Ziekenhuis te Sittard. In 1996 werd zij aangesteld als assistent onderzoeker aan de Erasmus Universiteit te Rotterdam, afdeling Orthopaedie. Onder leiding van prof. dr. J.A.N. Verhaar heeft zij fundamenteel onderzoek gedaan naar kraakbeenregeneratie. Van 1997 – 2001 werd zij opgeleid tot revalidatiearts in het circuit Sint Maartenskliniek – Canisius Wilhelmina Ziekenhuis te Nijmegen (opleiders: drs. R.A.J. Rijken en drs. H.J.M. van Kuppevelt) en werd zij op 1 maart 2001 ingeschreven in het specialisten register. De data van dit proefschrift heeft zij tijdens haar assistententijd verzameld. Van 2001 – 2004 werkte zij als fellow (50% klinische werkzaamheden en 50% onderzoek) Revalidatie Geneeskunde aan het UMC St. Radboud te Nijmegen. Per 1 juli 2004 is zij staflid Revalidatie in het AMC te Amsterdam.

LIST OF PUBLICATIONS

1. de Haart M, van der Linden ES, de Vet HC, Arens H, Snoep G. The value of computed tomography in the diagnosis of grating scapula. Skeletal Radiol. 1994;23(5):357-9.
2. de Haart M, Marijnissen WJ, van Osch GJ, Verhaar JA. Optimization of chondrocyte expansion in culture. Effect of TGF beta-2, bFGF and L-ascorbic acid on bovine articular chondrocytes. Acta Orthop Scand. 1999;70(1):55-61.

3. Dault MC, de Haart M, Geurts AC, Arts IM, Nienhuis B. Effects of visual center of pressure feedback on postural control in young and elderly healthy adults and in stroke patients. Hum Mov Sci. 2003;22(3):221-36.
4. de Haart M, Geurts AC, Huidekoper SC, Fasotti L, van Limbeek J. Recovery of standing balance in postacute stroke patients: a rehabilitation cohort study. Arch Phys Med Rehabil. 2004;85(6):886-95.
5. Den Otter AR, Geurts AC, de Haart M, Mulder T, Duysens J. Step characteristics during obstacle avoidance in hemiplegic stroke. Exp Brain Res. 2005;161(2):180-92.
6. de Haart M, Geurts AC, Dault MC, Nienhuis B, Duysens J. Restoration of weight-shifting capacity in patients with postacute stroke: a rehabilitation cohort study. Arch Phys Med Rehabil. 2005;86:755-62.
7. Geurts AC, de Haart M, van Nes IJW, Duysens J. A review of standing balance recovery from stroke. Gait and Posture. In press.
8. de Haart M, Beelen A, Duysens J, Geurts AC. Selected posturographic parameters are associated with gait dependency in patients with postacute stroke. Submitted.
9. Roerdink M, de Haart M, Donker SF, Geurts AC, Beek PJ. Dynamical structure of postural sway fluctuations: findings from stroke patients. Submitted.