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Review

A review of standing balance recovery from stroke

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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.

Keywords: Posture; Balance; Recovery of function; Stroke; Rehabilitation

Contents

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1. 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 in patients 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.

2. 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 non-paretic leg as well as increased spontaneous postural sway, most prominently in the frontal plane, are among the most characteristic consequences of incompletely recovered hemi paresis [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 (>0.4 Hz) [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.

2.1. 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 post urography. 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). 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.

2.2. 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

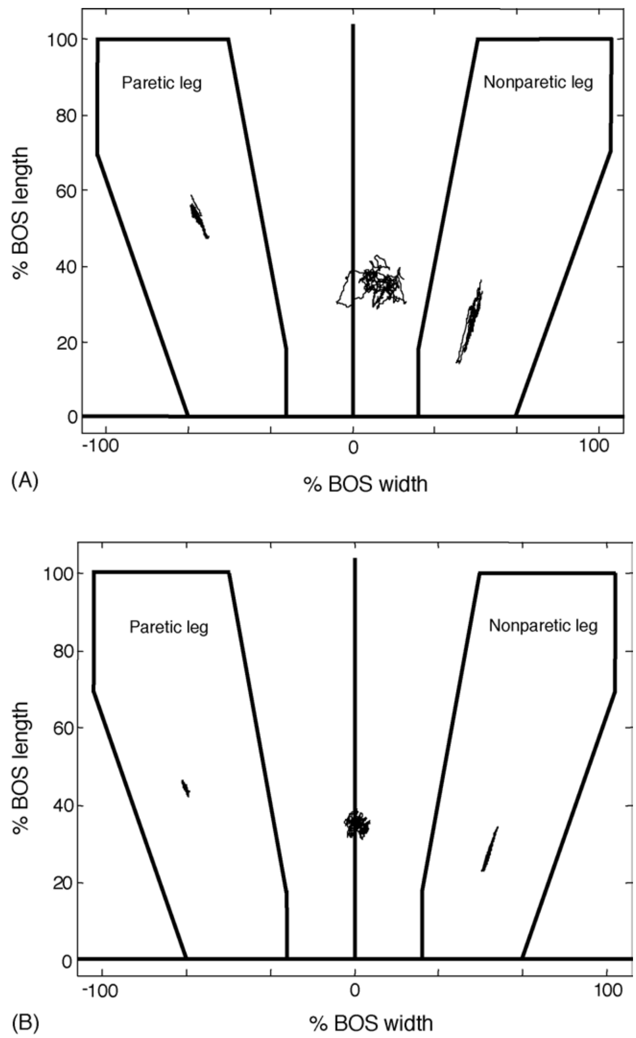

Fig. 1. The COP trajectory for each foot separately and for both feet together ('overall COP') during unperturbed standing with eyes open for 30 s in a 48-year old male, who had sustained an infarction in the right-hemisphere 1 month before (A). Note the weight-bearing asymmetry reflected in the lateral 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.

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.

2.3. 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.

3. 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].

3.1. 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 who 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 did 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].

3.2. 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.

4. 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].

4.1. 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 × 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.

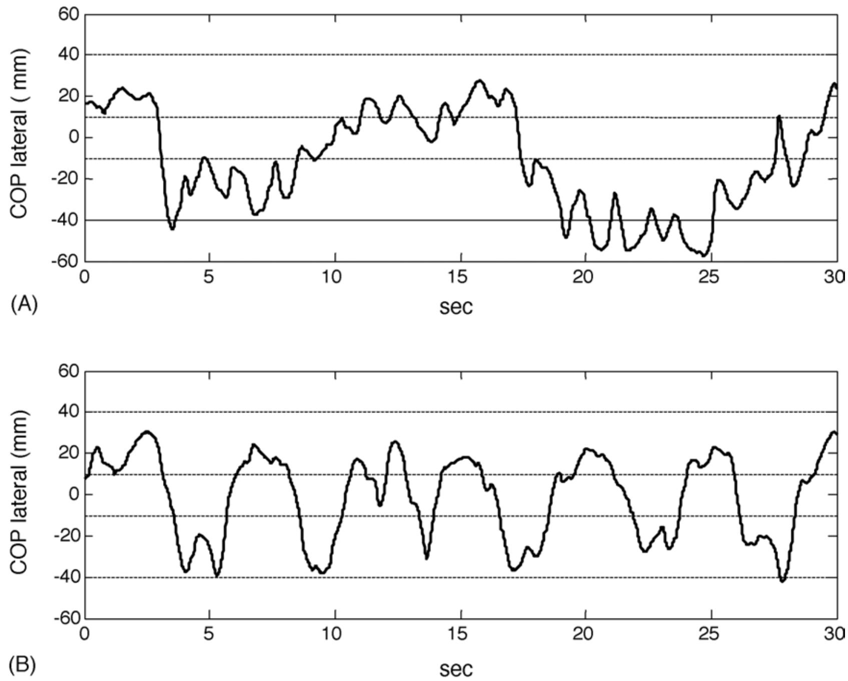

Fig. 2. The lateral COP trajectory (positive values towards the right, negative values towards the left from the sagittal midline) during voluntary lateral weight-shifting for 30 s in a 65-year old male, who had sustained an infarction in the left cerebral hemisphere. The interrupted lines (at 10 and 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).

Subjects were instructed to make as many weight shifts as fluently as possible in 30 s (see Fig. 2). 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].

4.2. 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 min 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.

5. 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 organisation 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 their 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] hypothesised 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.

5.1. 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 suggests 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].

6. 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'.

6.1. 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 ($r_s = -0.37$ to -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.

6.2. Influence of hemi-neglect

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 contra-lesional 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].

7. 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 of 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.

7.1. 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.

7.2. 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.

7.3. 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 have 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.

7.4. 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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