

Falls in individuals with stroke

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Abstract—Stroke survivors are at high risk for falls in all post-stroke stages. Falls may have severe consequences, both physically and psychosocially. Individuals with stroke have an increased risk for hip fractures, and after such a fracture, they less often regain independent mobility. In addition, fear of falling is a common consequence of falls, which may lead to decreased physical activity, social deprivation and, eventually, loss of independence. Important risk factors for falls are balance and gait deficits. Stroke-related balance deficits comprise reduced postural stability during quiet standing and delayed and less coordinated responses to both self-induced and external balance perturbations. Gait deficits include reduced propulsion at push-off, decreased hip and knee flexion during the swing phase, and reduced stability during the stance phase. Interventions addressing these deficits can be expected to prevent falls more successfully. Preliminary evidence shows that task-specific exercise programs targeting balance and gait deficits can indeed reduce the number of falls in individuals with stroke. Technological advances in assistive devices are another promising area. More research is needed, however, to provide conclusive evidence of the efficacy of these interventions regarding the prevention of falls in individuals with stroke.

Key words: accidental falls, balance, cerebrovascular accident, fall circumstances, fall injuries, gait, postural control, prevention of falls, rehabilitation, stroke.

INTRODUCTION

Falls are the number one medical complication after acute stroke [1–2]. Furthermore, the high fall risk for

individuals with stroke is not only present in the acute phase, but it remains a considerable health concern throughout the poststroke life span. Because the incidence and prevalence of stroke increase as a result of ageing of the population [3] and the prevalence also increases as a result of continued improvement of poststroke life expectancy [4], the societal impact of falls in stroke is rapidly growing. The impact is primarily related to the physical and psychosocial consequences of falls, which can be devastating. For instance, individuals with stroke are much more likely to sustain a hip fracture due to a fall than people without stroke and more often lose independent mobility or even die after a hip fracture [5–6]. This finding makes falls and their prevention an important issue for every person involved in stroke care (neurologists, physiatrists, physiotherapists, nurses, and also caregivers at home) and in any of the poststroke stages.

Abbreviations: ADL = activities of daily living, AFO = ankle-foot orthosis, BBS = Berg Balance Scale, BOS = base of support, COM = center of mass, COP = center of pressure, EMG = electromyographic, FES = functional electrical stimulation, GRF = ground reaction force, RF = rectus femoris, STS = sit-to-stand, TA = tibialis anterior, TUG = Timed Up and Go.

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Although the clinical significance of falls in individuals with stroke is widely appreciated and has been underscored in many publications, attempts to prevent falls in this population are still very scarce. In this review, we will summarize the current knowledge on the epidemiology of falls in individuals with stroke, their suggested pathophysiological background, as well as directions for (the development of) interventions to prevent falls.

EPIDEMIOLOGY OF FALLS

This section summarizes the current literature on the epidemiology of falls in individuals with stroke. For three poststroke stages (during acute hospital care, inpatient rehabilitation, and living in the community), we describe fall incidence rates, fall circumstances, risk factors for falls, and consequences of falls, as well as some implications regarding the prevention of falls.

Rates

Both prospective and retrospective studies have consistently reported high fall rates in individuals with stroke. For comparison, in the general population of elderly people, ~30 percent fall at least once a year and ~15 percent fall twice or more [7–9], yielding an incidence rate of ~0.65 falls each person-year [10]. In the limited time that individuals with stroke are admitted in an acute care setting, 3.8 to 22.0 percent of the patients fall at least once [1–2,11], which makes falling the most frequent medical complication during hospitalization after stroke (~40% of all complications). The variability in these fall rates can be attributed at least partly to differences in length of stay. Expressed as fall incidence rates, they vary considerably less between studies, yielding 2.2 to 4.9 falls each person-year [1–2,11]. Compared with other pathologies, such as congestive heart failure and community-acquired pneumonia, the risk for hospital falls is more than doubled in acute stroke [1]. The incidence rates are remarkably high given the degree of surveillance and the proportion of patients bedridden with, consequently, little exposure to risky situations.

The reported rates of people falling during inpatient rehabilitation range from 10.5 to 47.0 percent [12–24], with 5 to 27 percent of patients falling twice or more [14–16,18–19]. Patients are most likely to fall during the first 3 weeks of rehabilitation [20–21]. The proportion of fallers as well as fall incidence rates (1.3–6.5 falls each person-

year) [14–16,18–21] varies considerably between studies, but particularly the incidence rates are, without exception, much higher than in the general population of elderly people.

In community-dwelling stroke survivors, fall incidents are very common as well. The proportion of fallers ranged from 23 to 34, 40 to 73, and 43 to 70 percent for a 3- to 4-month [12,25], 6-month [17,26–33], and 1-year follow-up [22,34–36], respectively. Fallers in the stroke population are also more likely to become repeat fallers than elderly people in the general population. Most studies report proportions of repeat fallers in stroke populations between 21 and 57 percent for a 6- to 12-month period [17,22,27–28,30–36]. Only two studies report proportions of repeat fallers similar to the general elderly population, but for a shorter follow-up period (11%–12% in 4–6 months vs 15% in 1 year) [25,29]. Obviously, from these numbers, fall incidence rates are also consistently high (1.4–5.0 falls each person-year) [25,28,30–33,36].

The differences in fall incidence rates between studies can be partly explained by stroke group characteristics. The variability in fall rates during inpatient rehabilitation is presumably related to differences in healthcare organization and stroke rehabilitation protocols between countries and even between regions and institutions. Differences in the number of days poststroke that patients are admitted to rehabilitation, the duration of their stay, the characteristics of patients, as well as the composition of the rehabilitation program are other potential factors contributing to the variability in fall data as reported in the literature. Furthermore, the higher fall rates are generally reported immediately after discharge from the hospital or rehabilitation clinic and for stroke populations with residual disabilities [17,22,32]. The lower rates, on the other hand, are more likely obtained from stroke survivor groups recruited from the community, also including less severely affected people [25,36]. Interestingly, falls occur more often early after discharge from the hospital or rehabilitation clinic [17,32,37], with incidence rates in the first 8 weeks reaching a staggering 8.7 falls each person-year [17]. This finding suggests that during inpatient rehabilitation, people may not be optimally prepared for the challenges they encounter in their living environment.

Circumstances

In contrast to the invariably high fall incidence rates in the various poststroke stages, fall circumstances show distinct differences between inpatient falls and community-dwelling stroke survivor falls. In the acute care setting, only one study on fall circumstances could be identified, which tried to capture the most frequent fall times and sites [11]. However, the observation that most falls occurred during the day and in the patient's room, toilet, or bathroom does not shed much light on the potential mechanisms that resulted in those falls. The lack of insight into fall mechanisms in this setting may also explain the very low proportion of fall incidents deemed preventable (17%) [1]. The nurse-to-patient ratio may seem an important factor in this respect; however, previous research failed to demonstrate any such association [38]. More detailed incident reports on the circumstances of falls may provide the information needed to successfully prevent falls in the acute care setting.

Circumstances of falls during inpatient rehabilitation have been described in the literature in more detail. Similar to the hospital falls, in this stage, falls also occur predominantly at daytime [15,18] and in the patient's own room [15,18,20–21,39] and lavatory [20]. Transfers are the most common activity leading to a fall [15,20], whereas only a few falls involve walking or exercising [15]. Hence, despite exploring the patient's limits of balance and gait abilities, physiotherapy to improve these motor capacities appears to be very safe in this respect. The large number of falls (58%) that occur when people act against instructions (e.g., he or she transferred or walked without the recommended supervision or aids) [15] is a particular problem during inpatient rehabilitation. These falls often concern patients with cognitive deficits, and in these patients, falls are difficult to prevent. When patients cannot be instructed properly, only strict individualized protocols on surveillance and assistance (e.g., for transfers) may be successful without largely restricting the patients' mobility. However, this approach places a large burden on available staff and may, therefore, be difficult to implement.

In community-dwelling stroke survivors, transfers are still a problem [17,25,32,34], but they are no longer the most common activity leading to falls. In this population, walking is the most frequently mentioned activity (39%–90%) at the time of a fall [17,25,29–30,32–33]. This finding is very similar to the usual fall circumstances in the general population of elderly people [8,40],

but in individuals with stroke, falls occur more often during walking indoors than outdoors [29–30,32–33], with extrinsic factors such as obstacles involved less frequently [25]. Furthermore, the ~2,800 steps a day taken by individuals with chronic stroke [41] shows that their physical activity level has dramatically decreased compared with the mean number of 6,565 steps a day (95% confidence interval: 4,897–8,233) in older adults [42]. Considering the high fall incidence rates and the major portion of falls that occurs during walking, we find that the risk for falls to each unit of walking activity is tremendously increased in individuals with stroke. These numbers and observations also point to disease-specific mechanisms leading to falls. As such, intervention strategies that have been developed and proven effective for community-dwelling elderly individuals without stroke cannot simply be copied to the population of individuals with stroke without making specific adjustments.

Risk Factors and Identification of People at Risk

Many studies have tried to identify risk factors for falls by comparing fallers to nonfallers or repeat (2+) fallers to non- and onetime fallers. Risk factors are generally similar for inpatient and community-dwelling individuals with stroke. One exception is transfer ability, which seems to be a more pronounced risk factor for inpatients [39]. This finding agrees with the reports that falls occur most frequently during transfers in this stage.

The most consistently reported risk factor is activities of daily living (ADL) functioning, with fallers more ADL dependent than nonfallers [17–20,27,29,34,43]. However, ADL scales capture the sum of deficits on very different domains. From these ADL scores, the deficit that most importantly contributes to the higher fall rates cannot be distinguished. Most studies that used more specific assessments (e.g., Berg Balance Scale [BBS] or Tinetti test) have identified balance and gait deficits as important fall risk factors [17,19,27,29,31,33,35], although in a few studies, balance tests failed to discriminate between fallers and nonfallers [30,36,44]. Furthermore, research has suggested that individuals with stroke are more likely to fall when walking requires substantial cognitive control (i.e., was less automated), because fallers are more often unable to walk and talk at the same time or slow down when performing a concurrent mental task [28,35,44]. At present, conclusive evidence exists for balance and gait deficits as fall risk factors in the general population of elderly people [10,45]. Most likely, disease-related deficits

in this domain of physical functioning also play a major role in the etiology of falls in individuals with stroke.

Disease-related mental factors (depression and cognitive deficits) [13,17,19–20,25,33,43,46] and sensory deficits [26,29] also likely contribute to increased fall risk in individuals with stroke. With respect to other potential risk factors, conflicting results have been reported on quadriceps strength [31,36], spasticity [29,35], and hemineglect [13,16–17,19,47]. In general, fallers are not likely to be older than nonfallers [13,21,27,29], do not suffer from hemianopia more often [19,26], do not have different stroke types and locations (with the exception of bilateral brain lesions [14]) or different sides of stroke [16,19,27,29], and do not differ from nonfallers regarding sex [13,19,29]. However, these studies may lack power to identify increased fall risk for relatively infrequent, but potentially very disabling, stroke locations (e.g., in the brainstem).

In line with research on fall risk in the general elderly population, several studies have aimed to identify stroke fallers. Researchers have identified people at risk mostly by means of composite test scores, incorporating many of the risk factors just discussed [12,14,16]. However, the predictive values of these composite scores are not substantially better than those obtained on the basis of single tests (BBS, Timed Up and Go [TUG], Stops Walking When Talking [28,35]). In fact, none of these tests has been able to convincingly predict the patient with stroke who is going to be a faller and who is not. The rationale for identifying future fallers is that, to be most efficient and cost-effective, preventive measures need to be directed only to those people at the highest risk. This approach is appropriate indeed for the general elderly population in which a relatively small proportion of subjects accounts for the majority of falls. However, given the impressive fall rates in the stroke population, every patient with residual disabilities may be considered at increased risk, hence, directing resources to develop and evaluate preventive measures may be more beneficial than to optimize identification of stroke fallers.

Consequences

Falls are much a concern because of their consequences, both physically and psychosocially. The reported proportions of falls in individuals with stroke leading to injuries vary from 8 percent to as much as 69 percent [15–18,20,30,32,36,48], but the injuries are usually mild (bruises or grazes). Fracture rates vary from 0.6 to 8.5 percent

[2,6,11,17–18,20,22,48]. These overall fracture rates are not higher than in the general elderly population (~5%) [10], but importantly, a large proportion of fractures in persons with stroke (45%–59%) involves the hip [5–6,49], usually on the paretic side (76%–82%) [50–51]. One study reports that of the people with hip fractures, the prevalence of stroke is 27 percent [5] compared with a prevalence of 2 to 10 percent in the general population (for ages 55–64 to >85 years) [3]. The reported odds ratios (relative to the general population) for hip fractures in individuals with stroke are 3.8 for people aged >70, 3.0 for 70 to 80, and 2.1 for >80 [6]. The increased hip fracture risk is partly due to the high fall incidence rates, but falls are also more likely to cause hip fractures due to loss of bone mineral density (most prominently on the affected side), which is a common long-term complication poststroke [52–54]. Individuals with stroke are more likely to sustain a hip rather than a wrist fracture [6], probably because they are less able to break a fall by stretching out the affected arm. A second explanation for hip fractures outnumbering wrist fractures is that frontal plane balance is relatively severely affected in individuals with stroke [55], which presumably results in more frequent falls to the side, with direct impact to the hip.

Individuals with stroke have not only an increased risk for hip fractures but also more severe consequences. After a hip fracture, they are reported to regain independent mobility in only 38 percent of the cases, whereas this finding was true for 69 percent of the general population [5]. Mortality rates are found to be doubled 3 months after surgically treated fractures in individuals with stroke (10% vs 5% in hip fracture patients without stroke) [51].

Although these physical consequences are significant and usually attract the most attention, psychosocial consequences can be significant as well. Of the individuals with stroke who have fallen, many develop a fear of falling (88%) [22]. This fear of falling is related to balance and gait deficits [56] and often leads to reduced physical activity and deconditioning. In fact, 44 percent of stroke fallers report restriction of activity after the fall [32]. Given the very low physical activity and cardiovascular fitness levels already near the lower limit of those required for basic ADL [41,57], further activity reduction and deconditioning due to fear of falling can easily lead to loss of independence in individuals with stroke.

Social deprivation is another consequence of falls and the fear of falling. Forster and Young showed that

patients who had fallen at least twice were less socially active than before these falls [17]. In addition, they found that caretakers of fallers were more stressed. These caretakers, especially when they were the main caretakers, were more concerned about the patients falling, which possibly limited patients' social activities as well. Furthermore, depression not only is a risk factor for falls, it can also be a consequence of falling [17]. Depression and lower social activity can further accelerate the reduction of physical activity and deconditioning and thereby increase the risk for falling. The interactions between risk factors, falls, and consequences of falls are summarized in **Figure 1**.

PATHOPHYSIOLOGY OF BALANCE AND GAIT DEFICITS

From the previous section, one can conclude that stroke-related balance and gait deficits, as identified by clinical assessments, contribute to the large number of falls in these patients. But what are the pathophysiological mechanisms underlying these deficits? With respect to maintenance of upright balance, three domains of balance abilities should be considered (**Table**).

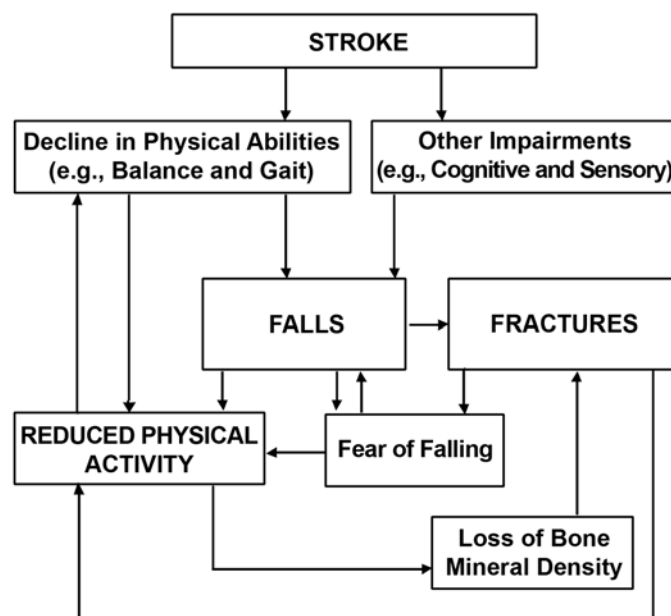


Figure 1. Interactions between risk factors, falls, and consequences of falls in persons with stroke.

First, one has to be able to stand quietly, without losing balance. The COM (vertical projection) of the body needs to be maintained well within the limits of the BOS. Second, one has to be able to voluntarily move the body (parts) to execute ADL without falling. When performing tasks in a stationary position (such as reaching or weight-shifting), a person must reposition the COM within the BOS. In a task in which the BOS changes position or size (such as a sit-to-stand [STS] movement or a step), the COM has to be adequately repositioned with the new BOS to not fall. Third, an external perturbation (e.g., movement of the support surface or a push) can move the COM toward the limits of the BOS (or beyond). Hence, one has to be able to react to these external forces with appropriately timed and scaled responses to maintain balance.

With respect to gait, safe and independent ambulation in everyday life includes the ability to walk over even surfaces as well as over challenging terrain (e.g., obstacles in the travel path). Walking over even terrain relies on a coordinated and rhythmic pattern of muscle activation, generating sufficient mechanical energy to produce progression of gait. During the swing phase of gait, one has to achieve sufficient clearance of the foot to prevent stumbling. Furthermore, postural stability during walking requires sufficient stance stability of the weight-bearing lower limb and adequate pre-positioning of the swinging leg and foot for weight acceptance. In addition, to walk safely over uneven terrain, one should be able to adapt the gait pattern in response to various environmental obstacles and constraints.

Clinical tests, such as the BBS, the Tinetti test, and various gait tests, focus on abilities in one or more of these domains, but they do not reveal the deficits underlying nonoptimal performance. The use of quantitative assessments is essential for one to understand the pathophysiology of these deficits. Such knowledge is fundamentally required for developing and evaluating targeted fall prevention and rehabilitation strategies. In the following paragraphs, we summarize the current literature on the pathophysiology of stroke-related balance and gait deficits. For more extensive reviews on this topic, see Geurts et al. [58], Olney and Richards [59–60], and Lamontagne et al. [61].

Quiet Stance

Assessments of postural stability are usually conducted with a force platform, which measures the ground reaction forces (GRFs). The point of application of the

Table.

Essential requirements for safe and independent balance and gait.

Balance	Gait
1. Quiet standing: Ability to maintain COM within BOS.	1. Walking over even surfaces: <ul style="list-style-type: none"> • Sufficient stance stability. • Rhythmic muscle activation pattern. • Sufficient mechanical energy. • Sufficient foot clearance during swing phase.
2. Self-induced perturbation: Adequate repositioning of COM within (stationary or moving) BOS.	2. Walking over uneven surfaces: Adaptations to environmental obstacles and constraints.
3. External perturbation: Adequate response to sudden displacements of COM (push-pull) or BOS (slip).	

BOS = base of support, COM = center of body mass.

GRFs is called the center of pressure (COP). This measure includes both an estimation (vertical projection) of the position of the body's COM and of the stabilizing torques exerted on the ground surface for one to maintain the COM within the BOS (kinetic regulation). The most frequently used characteristics of postural stability are body sway (in terms of COP amplitude, velocity, and frequency) and weight-bearing distribution (comparison between the amount of weight borne on each lower limb).

In general, such quantitative measures corroborate the results of clinical assessments, showing that individuals with stroke have impaired postural stability. They have more body sway [55,62–67], especially in the frontal plane, and they rely more on their nonparetic lower limb to maintain balance [55,63,66–71]. Depending on how sway is expressed, individuals with stroke show 1.5 to 5.0 times the amount of sway of nondisabled elderly individuals [55,62–63,66,70].

With respect to weight-bearing asymmetry, De Haart and coworkers found a 10 percent COP deviation from the midline in favor of the nonparetic lower limb [55]. Other studies looking at weight distribution also showed that the paretic lower limb carried about 40 percent of the body weight [63,72]. Recently, several studies looked at the COP movements for each lower limb separately, giving more detailed information about the kinetic regulation activity of each lower limb (i.e., the contribution of each lower limb to postural stability) [55,71]. De Haart and coworkers used the velocity of the COP of both lower limbs to calculate a kinetic regulation asymmetry quotient [55]. This quotient revealed that the kinetic contribution of the paretic lower limb was ~30 percent of the total kinetic regulation activity. Van Asseldonk and cowork-

ers determined the contribution of each lower limb on the basis of the ankle joint torques of each lower limb [71]. They concluded that the contribution of the paretic lower limb to the maintenance of balance is between 11 and 45 percent. In addition, they found that the contribution of the paretic lower limb to balance was much smaller than its contribution to weight-bearing. Thus, to precisely estimate the paretic lower-limb contribution to stance stability, one needs to account for joint torques.

Furthermore, quiet-standing tasks have been combined with visual deprivation or the addition of a secondary, cognitive task. In general, visual deprivation has little to no effect on weight-bearing asymmetry, but the increment in sway is larger in individuals with stroke than in nondisabled elderly people, especially in the frontal plane [55,63,66]. Apparently, individuals with stroke rely more on visual information for balance control [73], probably to compensate for impaired proprioceptive feedback. The reliance on visual input may point toward an impaired sensory integration or sensory reweighting [73–74]. The addition of a secondary cognitive task also affects postural control in individuals with stroke. It increases sway velocity as well as weight-bearing asymmetry in favor of the nonparetic lower limb [55,64]. This finding shows that postural control is less automated in this population.

Studies on the relationship of these postural impairments to the occurrence of falls in individuals with stroke have reported rather ambiguous results. Although Sackley found a significant relationship between increased body sway and the number of falls [75], the association was only weak ($r = 0.27$), indicating that less than 10 percent of the variation in the number of falls can be explained by

body sway. In the study by Jørgensen and coworkers [25], larger body sway was not found to be a significant risk factor for falls in everyday life. In contrast, other researchers found that stroke-related impairments in postural stability in reduced sensory information conditions coincide with a large increase in the number of falls during the assessments [74]. In addition, the lack of automaticity in postural control may also be a risk factor for falls in the stroke population, particularly because clinical tests (Stops Walking When Talking) point to the same direction [28,35,44].

Self-Induced Perturbations

Several studies have shown that the feed-forward balance control, as required for appropriate performance of self-induced perturbations, is impaired in individuals with stroke [76–79]. For instance, the ability to shift weight, particularly onto the paretic lower limb, is often reduced. De Haart and coworkers studied voluntary weight-shifting while patients moved their bodies rhythmically and laterally using visual feedback of their COP [76]. They took longer to transfer their weight from the nonparetic to the paretic lower limb than vice versa (4.3 s for a transfer to the paretic vs 3.5 s to the nonparetic lower limb). Nondisabled elderly people had symmetrical transfer times of 2.6 s. The target accuracy was also reduced in individuals with stroke. Other studies showed that patients had decreased maximal weight transfers to either direction during standing on two lower limbs, although the transfer to the nonparetic lower limb was less severely impaired. Individuals with stroke could shift ~65 percent of their body weight to the affected limb and 65 to 85 percent to the nonaffected lower limb [78–79], whereas nondisabled elderly people achieved maximal weight shifts of ~95 percent to either side [77–78].

Garland and coworkers used a rapid arm flexion movement (nonparetic side) as a self-induced balance perturbation [80]. In individuals with stroke, these arm movements induced larger sway amplitudes and higher velocities of sway (~40%) compared with nondisabled subjects. In addition, electromyographic (EMG) data revealed that muscle onset latencies were delayed by ~90 ms contralateral to the moving arm in the hamstrings and by ~35 ms in the ipsilateral hamstrings. Apparently, anticipatory muscle activation sequences (feed-forward control) are disrupted in individuals with stroke, especially in the most severely affected patients (e.g., low BBS scores). As a more challenging task, Cheng and

coworkers studied STS movements [81–82]. Their results showed that individuals with stroke are impaired in their STS ability, as indicated by longer movement duration, decreased rise-in-force rates, more asymmetrical weight-bearing, larger COP displacements in the frontal plane, and disrupted muscle activation sequences.

Impaired control of self-initiated balance perturbations may put individuals with stroke at risk for falls. For STS movements, Cheng and coworkers showed that STS parameters indeed differed between individuals with stroke and nondisabled controls and that stroke fallers also performed worse than nonfallers [81–82]. Fallers took longer to perform the STS movement, and they had reduced rates of rise in force and increased mediolateral COP excursions. In addition, a pattern of low-amplitude paretic tibialis anterior (TA) and premature or excessive soleus activity was also more frequently observed in fallers. These results indicate that impaired feed-forward postural control is indeed a risk factor for falls, although this relationship remains to be determined for other types of self-induced perturbations as well.

External Balance Perturbations

When balance is perturbed by an external force, responses to the perturbation are triggered by sensory input (somatosensory, visual, or proprioceptive). Hence, the control of postural stability in such situations relies more on feedback mechanisms than on feed-forward control. External perturbations are mostly presented by translations or rotations of the support surface [72,83] or by pushing the subject around the waist [84–86]. Compared with nondisabled elderly people, individuals with stroke generally have delayed and reduced muscle (and, consequently, kinetic and kinematic) responses to external perturbations [72,85,87–90]. Marigold and coworkers collected EMG data from leg muscles (TA and gastrocnemius) and found that muscle responses in the paretic leg to sudden support surface movements were delayed by ~15 and ~26 ms, respectively [72]. In a similar task, Ikai and coworkers found that individuals with stroke had delayed kinetic response times (~15–30 ms) in the paretic lower limb [87], whereas the sound lower limb showed no delay. Furthermore, individuals with stroke have less coordinated responses, as evidenced by disrupted muscle activation sequences [85].

The stroke-related impairments in the characteristics of responses to external balance perturbations increase the risk for falling. Marigold and Eng showed that individuals

with stroke who fell during a support surface translation (assigned as fallers) had more delayed (12–35 ms) muscle responses in paretic TA, biceps femoris, and bilateral rectus femoris (RF) compared with those who did not fall during the same perturbations [83]. Although all the patients and the controls had a distal to proximal muscle activation sequence, the intervals between proximal (RF) and distal (TA) muscle onset were longer in fallers (~45%–50%) in both the paretic and nonparetic lower limb. The relationship between response characteristics in individuals with stroke and fall risk in everyday life has not yet been investigated.

Level Walking

Although gait patterns may vary greatly between patients with stroke, some general characteristics of stroke gait patterns can be identified. Overall, walking speed, as the most frequently used (clinical) measure to quantify gait impairments, is substantially reduced in individuals with stroke compared with nondisabled controls (mean \pm standard deviation from 0.39 ± 0.26 m/s to 0.78 ± 0.38 m/s for patients vs 1.15 ± 0.21 to 1.40 ± 0.23 m/s for control subjects) [91–95]. The propulsive forces required for gait progression are mainly generated during the push-off phase [96]. Hence, stroke-related gait deviations during this phase can be expected to be responsible for the lack of progression. With respect to the kinematics during the late stance phase (which corresponds to push-off), individuals with stroke have decreased paretic hip extension, knee flexion, and ankle plantar flexion angles [59]. Furthermore, EMG activity of the calf muscles is substantially reduced in this phase of the step cycle [97–99]. This lower activity reduces plantar flexion moment at the ankle joint and, consequently, reduces push-off power [92,100]. Individuals with stroke try to compensate for this lack of push-off by an increased hip flexion moment during early swing (pull-off) [100–102] or an additional hip abduction moment at toe-off in the paretic lower limb [103]. These mechanisms can only partly compensate for the loss of push-off, mainly because hip muscle strength is reduced as well [104–105]. As a second compensatory mechanism for the reduced paretic push-off, individuals with stroke increase the nonparetic push-off [106]. Despite these compensations from both the paretic and nonparetic lower limb, they mostly do not achieve normal walking speeds.

The paretic swing phase also shows some characteristic deviations in individuals with stroke. These devi-

ations include decreased ankle dorsiflexion (foot-drop) [107–108] and knee flexion angles [109–111]. Ankle dorsiflexion angles are reduced, because individuals with stroke are often less able to (selectively) activate the TA muscle and may also have premature calf muscle activation [98–99,112]. The smaller knee flexion angles during swing (partly) depend on the knee flexion velocity during push-off [110]. Goldberg and coworkers have shown that the calf muscles importantly contribute to knee flexion velocity during push-off [110]. As such, the lack of push-off power in individuals with stroke not only slows walking speeds but also reduces flexion angles during early swing. The lack of swing lower-limb flexion leads to insufficient foot clearance, which puts patients at risk for stumbling and falling. Patients usually try to compensate for this lack of toe clearance by circumduction of the lower limb [106,108], pelvic tilt on the paretic side [106,109], and trunk lateral flexion toward the nonparetic side [113].

Finally, gait stability is impaired in individuals with stroke. At the end of the swing phase, decreased ankle dorsiflexion and reduced knee extension cause them to land on the forefoot more frequently [59]. In combination with the premature and excessive calf muscle activity in the paretic leg [98–99], this joint angle configuration may result in a small (forefoot) BOS during the single-support phase, which reduces stance stability. Furthermore, trunk excursions in the frontal plane are increased in individuals with stroke [113] and the distance between the body COM and the paretic foot (BOS) during single support is increased compared with nondisabled subjects [61]. The COM is projected well outside the BOS, thereby reducing stance stability. The COM is closer to the nonparetic lower limb, which indicates that the paretic lower limb contributes less to weight-bearing support compared with the nonparetic lower limb. This finding is consistent with the asymmetries in weight-bearing and kinetic regulation activity as observed during quiet stance. Because the COM is located medially of the paretic BOS, the body “falls” back to the nonparetic lower limb. Consequently, the subsequent nonparetic stance phase has to be initiated more quickly to prevent falling. This early landing is also reflected in the asymmetric stance durations as observed in individuals with stroke [106,108]. Other studies have suggested that increased levels of coactivation of the upper lower-limb muscles (biceps and RF) may compensate for the lack of stance stability [112,114]. Increased step widths, which are frequently observed in individuals

with stroke, are also thought to be a compensation for their reduced stability during gait [106].

Furthermore, several studies have shown that individuals' gait parameters, such as velocity, stride time and length, and the duration of the double-support phase, are affected by adding a cognitive task [44,115–116] or when walking in an environment with many distractions, such as a mall [117]. This finding implies that stroke-related gait impairments also include a reduced automaticity of walking.

Although previous research has not directly associated any of these gait parameters (except walking speed) with fall risk in individuals with stroke, studies in nondisabled elderly people have shown that several gait deviations contribute to the risk for falling. For instance, Chen, Barak, and coworkers reported that fallers had smaller ankle plantar flexion and hip extension angles, at a range of matched walking speeds, during late stance compared with nonfallers [106,118]. Chen, Lee, and coworkers showed that ankle plantar flexion moments were reduced and hip flexion moments were increased in fallers [106,119]. Hence, these gait deviations might put individuals with stroke at risk for falling, particularly because most falls occur during walking.

Complex Walking Skills

The ability for persons to adjust their gait pattern in response to environmental demands is a prerequisite for safe walking in everyday life. In studies investigating such complex walking skills, obstacle avoidance paradigms have been used most frequently. Said and coworkers conducted an experiment in which individuals with stroke walked on a walkway and had to step over a stationary obstacle [120–121]. They suggested that individuals with stroke used a more cautious strategy to step over the obstacle with higher toe clearance of the lead limb (i.e., the lower limb that crosses the obstacle first), smaller postobstacle distances, and greater step times than nondisabled subjects [120]. Despite this presumed safety strategy, they observed more obstacle contacts in individuals with stroke than in nondisabled controls, who did not contact the obstacle at all. Although the failure rate was lower when the nonparetic lower limb crossed the obstacle first (5.7% vs 11.2% with paretic lower limb first), the patients exhibited no preference for the paretic or nonparetic lower limb as the lead limb. The use of both high (8 cm) and wide (8 cm) obstacles resulted in different reasons for failures. When the high obstacle was

presented, the main reason for failure was postural instability (reaching the handle bars or the spotter), whereas with wider obstacles, patients usually hit the obstacle with the toes of the leading foot [120].

In a subsequent study, Said and coworkers also looked at the trail limb [122]. They found that toe clearance of the trail limb was reduced, which increases the risk for tripping. Another study by the same research group demonstrated increased anterior-posterior separation of the COP and the COM in individuals with stroke stepping over the obstacle with the nonparetic lower limb [123]. This result indicates that individuals with stroke have impaired postural stability during obstacle crossing.

Compared with the disease-related deficits in such a relatively simple obstacle avoidance task, individuals with stroke are even more impaired when they have to avoid obstacles that suddenly appear before them. Failure rates in obstacle avoidance under time pressure are considerably higher in individuals with stroke (14%–28%) than in nondisabled people [124–126]. Patients are particularly unsuccessful in the most time-critical condition [124]. This finding can be attributed primarily to their dramatically delayed response onset latencies. The observed onset latencies in the biceps femoris, which is the prime mover in this task, were ~220 ms in individuals with stroke versus ~120 ms in elderly people performing the same task [125–126]. These results indicate that in individuals with stroke, gait adjustments in response to an obstacle are no longer controlled by automation. Instead, they have to cognitively control such gait adjustments [126].

The direct relationship between obstacle avoidance parameters and falls in individuals with stroke has not yet been studied. In nondisabled elderly people, however, success rates on obstacle avoidance under time pressure distinguished repeat fallers from non- or onetime fallers [127]. Because individuals with stroke commonly complain that walking over uneven terrain requires their full attention to not fall, impaired obstacle avoidance abilities may put them at risk for falls as well. In the “Epidemiology of Falls” section, we have described the tremendous reduction in physical activity levels in individuals with stroke. Strategies to increase these activity levels would typically include walking outdoors more often, which also introduces a higher probability of encountering such challenging walking environments. Hence, optimizing complex walking skills is important for increasing physical activity levels in individuals with stroke without a concomitant increase in the number of falls.

Summary

In conclusion, individuals with stroke often show balance deficits, such as reduced postural stability during quiet standing and delayed and less coordinated responses, to both self-induced and external balance perturbations. Gait deficits include reduced propulsion at push-off, decreased leg flexion during the swing phase, reduced stability during the stance phase, and reduced automaticity of walking. The ability to adjust the walking pattern to environmental obstacles and constraints is also severely affected in persons with stroke. Although these deficits have rarely been investigated in relation to the risk for falls and are seldom the only cause of a fall, they are very likely to play a major role in the usually multifactorial etiology of falls.

PREVENTION OF FALLS

In the "Epidemiology of Falls" section, we highlighted the vast amount of scientific articles describing the impressive numbers of individuals with stroke who fall, irrespective of the poststroke stage. In the etiology of falls in the stroke population, balance and gait deficits play a major role. We also extensively studied the pathophysiological background of these deficits, as summarized in the previous section. In contrast, few studies have addressed how falls in individuals with stroke may be prevented, particularly during inpatient rehabilitation. Black-Schaffer and coworkers indicated that preventive measures may comprise [128], for example, adequately supervising patients; training of strength, balance, and cognition; minimizing sedatives and diuretics use; and using alarms and restraints. However, the efficacy of these measures regarding fall incidence rates during rehabilitation has not yet been adequately investigated. Because many falls during rehabilitation are related to transfers [15,20] and to moments in which the patient (usually with cognitive deficits) is acting against instructions [15], apparently, an intervention strategy should at least incorporate specific and individualized preventive measures targeting those circumstances to be successful.

After patients are discharged from inpatient rehabilitation and in the chronic poststroke stage, falls are most frequently related to loss of balance during walking. These falls occur despite gait and balance training being a major part of both rehabilitation [129] and community physiotherapy poststroke [130]. This finding raises the

questions, Are these falls after stroke inevitable and are the present therapy protocols sufficiently effective in preventing the falls? In other words, do the very high fall incidence rates early after discharge mean that the current rehabilitation programs do not optimally prepare the patient for adequate functioning in his or her living environment? And would the usual community-based care for individuals with stroke (e.g., physiotherapy) require revision in terms of referral criteria and intervention protocols? A randomized controlled trial by Green and coworkers indeed showed that "usual" community-based physiotherapy in individuals with chronic stroke does not reduce the number of falls [130]. We must note that the stroke-related problems and the corresponding interventions in this study were rather diverse, and as such, the study protocol did not specifically target the reduction of falls. On the other hand, because the prescribed interventions often targeted balance and gait problems, why did they not result in fewer falls? The answer may be that in this trial, the intensity of the total physiotherapy treatment (median of three sessions) was not sufficient to prevent falls.

Beneficial effects of targeted training programs, however, suggest that even in chronic stroke, patients have some residual capacity that can be used if the appropriate stimuli are administered. Specific exercise programs (ranging from 9 to as many as 80 sessions) have repeatedly been shown effective in improving balance and gait abilities [131–143]. Unfortunately, despite training, disease-related deficits will persist in many stroke survivors. As such, a proportion of falls in individuals with stroke may indeed be inevitable and these patients will probably continue to fall more often than nondisabled elderly people. However, the evidence is growing that the number of falls in individuals with stroke can be substantially reduced as well. In this section, we will focus on specific exercise interventions and technological advances in assistive devices as two options that may be most promising in this respect.

Exercise Interventions

Exercise programs that are based on knowledge of the pathophysiology of stroke-specific balance and gait deficits can be most successful in preventing falls. Generally, research has suggested that task-specific exercises would be most beneficial for individuals with stroke, because this approach is thought to drive neural plasticity [144].

Vearrier and coworkers evaluated such a task-specific training program (10 sessions of 6 hours each) in a group

of 10 individuals with chronic stroke [145]. Exercises targeted the various domains of balance and gait abilities that were described in the previous section and comprised, for instance, balancing on various support surfaces, weight-shifting, side-stepping, and walking over obstacles. Balance abilities (BBS and the time to stabilize after an external perturbation), balance confidence, and activity levels increased in these participants. Fall incidence rates during the 1-year follow-up period declined compared with those in the year before participation. The finding that the number of falls decreased and activity levels increased is particularly important, because theoretically, a reduction in fall rates could also be achieved by reduced exposure (reduced physical activity, **Figure 2**). The combination of results from this study indeed shows the benefit of such training.

We must note, however, that in the study by Vearrier and coworkers [145], preintervention fall incidence rates were obtained retrospectively over a 1-year period. This method of fall registration is rather unreliable because of substantial recall bias. Furthermore, no control group existed. Hence, the reduction in the number of falls being

partly due to a Hawthorne effect cannot be excluded, particularly because the follow-up fall incidence rate of 0.3 falls each person-year is even lower than in the general population of elderly people [10].

Another task-specific training program, consisting of 30 sessions of 1 hour, was developed by Marigold and coworkers and evaluated in a randomized controlled trial [146]. The task-specific exercises in this program were targeted to improve quiet-stance stability in various postures (feet apart, tandem, or one-foot stance), responses to self-induced (e.g., weight-shifting, STS) and external postural perturbations (patients being pushed in a controlled and safe manner), and walking with various challenges (e.g., different step lengths and speeds, tandem walking, obstacle crossing). This “agility” program was combined with multisensory training, because the various tasks were also performed with eyes closed and on a compliant surface (foam). Multisensory training is an important addition, as compared with training under “normal” circumstances; such training has previously shown larger gains in balance abilities [141–142].

In the study by Marigold and coworkers [146], participants in the agility program markedly improved clinical measures of balance and gait (BBS and TUG) and in balance confidence and health-related quality of life. Laboratory assessments demonstrated that participants also improved neurophysiologically, because faster responses were observed in both self-initiated (stepping) and externally triggered (support surface translation) postural perturbations. These improvements were larger than those observed in the control group. Importantly, the faster responses (particularly in RF) coincided with a significant reduction in the number of external perturbations that resulted in falls. Similar improvements in the intensity of perturbations that could be sustained without loss of balance have been reported as a result of a 15-session training program on a translating platform [147]. These results suggest that exercises to improve responses to external perturbations are an important component of stroke training programs.

During the 1-year follow-up fall registration, fall incidence rates in the agility group were 1.20 falls each person-year, versus 3.12 in the control group. Although this result was a major reduction, the study lacked power ($N = 40$) to identify a significant difference between groups in this outcome measure. The observed difference in reduced fall incidence rates between groups may, however, be somewhat diluted. People in the control group were

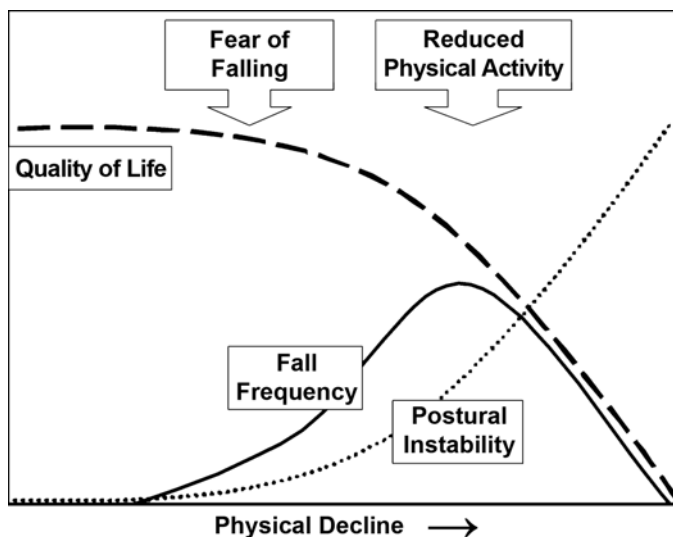


Figure 2.

Interplay between physical decline, fall frequency, postural instability, and quality of life (QOL) in persons with stroke. Reducing fall frequency is not necessarily good when achieved by reducing physical activity. In this case, it will lead to further physical decline, with reduced postural stability and QOL. Beneficial reduction in fall frequency, leading to better QOL, should coincide with improved postural stability, decreased fear of falling, and preserved or increased physical activity.

offered an intervention program (stretching and weight-shifting) of the same duration, and they also markedly improved many of the outcome measures. Hence, the stretching and weight-shifting training cannot be regarded as a “sham” intervention, because they may have reduced fall incidence rates in the control group as well.

Based on the results from Vearrier and coworkers [145] and Marigold and coworkers [146], agility training programs may indeed be effective in preventing falls in the chronic stroke population. This suggestion is further supported by positive results from similar fall prevention interventions in the general elderly population [148–149]. The task-specific nature of the exercises in these programs warrants optimal generalization of training results to daily life. Also important is including task manipulations that simulate the complexity of daily living, such as practicing with eyes closed, on unstable surfaces, and while concurrently performing a secondary task. The current stroke rehabilitation programs do not consistently include such components. As such, the very high fall incidence rates early after discharge suggest that patients are not sufficiently prepared for safe functioning in complex daily environments. The efficacy of fall prevention exercise programs, based on the principles mentioned in this section, is therefore expected to be even better when the program is administered near time of discharge from inpatient rehabilitation.

Thus far, only one research group has investigated whether an additional training program during inpatient rehabilitation (2–4 months poststroke) could reduce the number of patients falling during a 6-month follow-up period [150–151]. After participation, only 17 to 18 percent of the intervention group fell compared with 42 percent [150–151] in the control group. These results show that the final stage of inpatient stroke rehabilitation may indeed be the perfect moment to administer an intervention to prevent falls.

Assistive Devices

Persons with stroke frequently use assistive devices, such as walking aids and ankle-foot orthoses (AFOs), to improve the quality, stability, and/or efficiency of walking. The use of walking aids has also been suggested to prevent falls in this population [30]. Several studies have shown that both canes and AFOs improve important gait characteristics in individuals with stroke, such as walking velocity, stride length [109,152], and muscle activation patterns [153]. These improvements may therefore help

reduce the number of falls, although the beneficial effects of these devices with respect to the risk for falls in persons with stroke are still to be evaluated in intervention studies.

Recent advances in rehabilitation technology offer another promising avenue for restoring gait, possibly reducing the number of falls as well. Functional electrical stimulation (FES), particularly of the peroneal and tibial muscles, was introduced in 1961 by Liberson and coworkers [154], but a couple of decades passed before technical and ergonomic problems were solved to such an extent that the technique became available to larger populations of individuals with stroke. Beneficial effects of FES with respect to gait velocity are well established already [155–157], but recent studies [158–159] have also shown that quality and safety of walking in individuals with chronic stroke have substantially improved. Daly and coworkers observed substantially improved gait kinematics in stroke survivors by electrically stimulating various lower-limb muscles through intramuscular electrodes [158]. Hausdorff and Ring recently evaluated the efficacy of an external FES device in hemiparetic patients with a drop foot [159]. They showed that not only gait speed (both on level walking and on an obstacle course), gait symmetry, and stride time variability improved but also the number of falls reduced significantly. Only two falls (in 24 participants) were recorded during the 8 weeks that the patients used the FES device, versus 24 falls during the 2 months before inclusion in the study. These results demonstrate the major role of gait deficits in the etiology of falls in individuals with stroke. However, more importantly, they also indicate the tremendous benefits that may be expected with technology-assisted restoration of gait.

CONCLUSIONS

The topic of falls in individuals with stroke has received considerable attention in the scientific literature. Epidemiologic studies have shown that survivors of stroke are at high risk for falls in all poststroke stages. In the etiology of falls, stroke-related balance and gait deficits play an important role. Although many studies have been conducted to identify the pathophysiological mechanisms underlying these deficits, only a few studies have directly related more fundamental measures of balance and gait to the risk for falling in persons with stroke. More knowledge on such relations could be instructive in developing or improving intervention strategies. So far,

only a few studies have evaluated the efficacy of interventions to prevent falls in persons with stroke. Task-oriented exercise programs are the most promising in this respect, but larger randomized controlled trials are needed to provide more conclusive evidence. Furthermore, the most appropriate moment at which such programs should be administered to patients remains to be determined. Technological advances in assistive devices are another promising area, but evidence on the efficacy of these devices regarding the prevention of falls is still very preliminary. Hence, a clear need exists for future studies on interventions to prevent falls. We expect that this review will further direct research in tackling the major problem of falls in person with stroke.

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