Associations between changes in gait parameters, balance, and walking capacity during the first 3 months after stroke: a prospective observational study

Ole Petter Norvang MSc, PT, Torunn Askim PhD, PT, Thorlene Egerton PhD, PT, Anne Eitrem Dahl MSc, PT, and Pernille Thingstad PhD, PT

Department of Neuromedicine and Movement Science, NTNU-Norwegian University of Science and Technology, Trondheim, Norway; Department of Physiotherapy, St Olavs Hospital, Clinical Services, Trondheim, Norway; Department of Physiotherapy, Centre for Health Exercise and Sports Medicine, University of Melbourne, Melbourne, Australia

ABSTRACT
Background: Independent ambulation is a common rehabilitation goal after stroke, requiring adequate balance and efficiency of gait. Spatiotemporal gait parameters are expected to improve in the first 3 months and their association with balance and efficiency of gait may provide useful insights into the recovery of safe and independent mobility.

Objective: Examine the associations between changes in spatiotemporal gait parameters, balance, and walking capacity during the first 3 months after stroke.

Methods: This prospective observational study included participants diagnosed with stroke. Within the first 2 weeks after stroke onset and again 3 months (±2 weeks) later, gait was assessed using a GAITRite mat at self-selected gait speed, balance using the Berg Balance Scale (BBS), and walking capacity using the 6-minute walk test (6MWT). Changes in gait parameters, balance, and walking capacity were assessed using paired sample t-tests, and linear regression analyses were used to assess associations between changes in spatiotemporal gait parameters, BBS, and 6MWT.

Results: Seventy-nine participants (mean (SD) age 75.4 (8.5) years; 44 men) were included. Gait parameters, balance, and walking capacity all improved during follow-up. The bivariate regression analyses showed associations between improvements in all gait parameters, except walk ratio, with improvement in balance, and in all gait parameters with improvement in walking capacity. Only gait speed was associated with balance (13.8 points, 95% CI 0.5, 27.8, p = .0042) and walking capacity (256 m, 95% CI 173,340, p < .001) in the multivariate analyses.

Conclusion: Improved spatiotemporal gait parameters were associated with improved balance and walking capacity within the first 3 months after stroke.

Introduction

For older people, the ability to walk without the fear of falling is strongly associated with health-related quality of life (Stenhagen, Ekstrom, Nordell, and Elmstahl, 2014). With most spontaneous recovery taking place the first months after stroke (Jorgensen et al., 1995), an early and adjusted rehabilitation is important to regain independence. Following stroke, independent ambulation is reported to be the most frequent self-stated rehabilitation goal (Bohannon, Andrews, and Smith, 1988; Duncan et al., 2007). Walking with adequate postural stability to be safe and avoid falls and a level of gait efficiency that enables a functional level of walking capacity should be a focus in post-stroke rehabilitation (van Ooijen et al., 2015).

Gait speed is well documented as a marker for health and function and is one of the most common and recommended overall measures of gait for older adults (Cummings, Studenski, and Ferrucci, 2014). Following a stroke, most people improve their gait speed during the first 3 months (Fulk, He, Boyne, and Dunning, 2017; Wonsetler and Bowden, 2017), and this improvement is associated with improved community ambulation (Lord et al., 2004; van de Port, Kwakkel, and Lindeman, 2008). However, improved community ambulation also relies on adequate balance and walking capacity (van de Port, Kwakkel, and Lindeman, 2008).

Gait speed is a nonspecific measure and tells us little about gait quality and strategies. Although gait speed is closely associated with other gait parameters, such as cadence, step length, time in single support and asymmetry (Brandstater, de Bruin, Gowland, and Clark, 1983; Roth et al., 1997; Wonsetler and Bowden, 2017), increased speed may not always be the result of improved quality of gait as faster walking may be achieved through developing compensatory strategies...
Impairments as asymmetry (Schroeder, Dhaher, 2013). Compensatory strategies may lead to lower safety or efficiency when walking (Olney and Richards, 1996; Weerdesteyn, de Niet, van Duijnhoven, and Geurts, 2008) and lead to reduced overall capacity and increased risk of falling. Exploring the relationship between other gait parameters and both balance and walking capacity may improve understanding of the importance of quality of gait (Thingstad et al., 2015), and guide rehabilitation following stroke.

Balance is a complex system, involving both motor, sensory, and cognitive components, interacting with each other and with surroundings. A deficiency in any of these systems following a stroke can lead to balance impairments (Zou et al., 2018), and may be related to gait impairments. Previous studies have reported decreased step length and time in single support on the affected side early after stroke (Cruz, Lewek, and Dhaher, 2009; Mizuike, Ohgi, and Morita, 2009; von Schroeder et al., 1995). This spatiotemporal gait asymmetry indicates decreased ability to shift body weight onto the affected side (Patterson et al., 2010; van Dijk et al., 2017). During walking, this reduced ability to shift body weight onto the affected side may be related to the same deficits in motor and/or sensory control systems involved in maintaining balance. Reduced balance control has previously been shown to be associated with gait asymmetry (Hendrickson et al., 2014). However, while most spatiotemporal gait parameters improve early after stroke, gait symmetry may require more targeted rehabilitation for many stroke patients (Patterson et al., 2015; Rozanski et al., 2019).

Gait efficiency is related to energy cost of walking. Following a stroke, compensatory strategies resulting from persistent gait impairments may increase energy expenditure (Awad et al., 2015; Bae et al., 2018; Farris, Hampton, Lewek, and Sawicki, 2015), leading to fatigue (Michael, Allen, and Macko, 2006), and affect walking capacity. For example, improved step length on the affected side may lead to less asymmetry and improve efficiency (Awad et al., 2015). Walk ratio, the ratio of step length to cadence, may be related to gait efficiency as there appears to be an optimal stride length–cadence relationship (Egerton, Danoudis, Huxham, and Iansek, 2011). For stroke patients, an improvement in walk ratio toward that reported for healthy adults (Sekiya and Nagasaki, 1998), would indicate that step length has increased relative to cadence, which may imply improvements in gait efficiency.

Several studies have investigated changes in spatiotemporal gait parameters after stroke (Forrester et al., 2014; Lee, 2015; Verma, Arya, Garg, and Singh, 2011). Spatiotemporal gait parameters have also been associated with both balance (Dobkin et al., 2014; Rose et al., 2018) and walking capacity (Awad et al., 2015; Farris, Hampton, Lewek, and Sawicki, 2015) in cross-sectional and longitudinal studies.

However, investigating how changes in spatiotemporal gait parameters are associated with changes in balance and walking capacity will add further to this enquiry and could provide useful insights into the recovery of safe and efficient gait following a stroke. The aim of this study was therefore to examine the associations between changes in primary and calculated spatiotemporal gait parameters with changes in balance and walking capacity during the subacute phase post stroke. We hypothesize that changes in gait speed, step length, time in single support, and single support asymmetry would be most highly associated with changes in balance, as improvements in these spatiotemporal gait parameters would suggest an improved ability to shift body weight from side to side. In addition, we hypothesize that gait speed, step length, cadence, step length asymmetry, and walk ratio would be most highly associated with walking capacity, as improvements in these spatiotemporal gait parameters would suggest a more efficient gait with less energy expenditure.

Methods

Design

This study used a prospective observation design, with an initial assessment within 14 days and a follow-up assessment 3 months (±2 weeks) post stroke. The study was approved by the Central Regional Committee for Medical and Health Research Ethics (REC number 2011/2517). Informed and written consent was obtained from all participants. As this was an observational study in a comprehensive stroke unit, health and safety were obtained in accordance with standard procedures in the 2010 Norwegian guidelines for the management of stroke (Norwegian Directorate of Health, 2017).

Study setting

All participants were being managed in an evidence-based comprehensive stroke unit that emphasized a multidisciplinary approach and early rehabilitation, with a special focus on early mobilization and independence in daily life. Those in need of rehabilitation after discharge were transferred to a rehabilitation program in accordance with standard procedures in the 2010 Norwegian guidelines for the management of stroke (Norwegian Directorate of Health, 2017). According to the guidelines, patients discharged directly at home
received further rehabilitation according to their individual needs. This typically consists of 45 minutes of physiotherapy per week in the patient’s home or at an outpatient clinic.

**Study population**

Between March 2012 and October 2014, people admitted to the stroke unit at Trondheim University Hospital, Norway, were screened for eligibility. Those living in the municipality of Trondheim, diagnosed with first ever or recurrent acute ischemic or hemorrhagic stroke were eligible for inclusion if, within 14 days post stroke, their modified Rankin Scale (mRS) score was 0–3 points (able to walk without personal assistance), they were capable of walking with or without walking aid and without support from another person for 10 m, scored 4–6 points on the item “orientation” on Scandinavian Stroke Scale (SSS) (correct on two out of three on time, place, and situation), suffered from stroke impairments scoring from 0 to 57 points on SSS (max score 58 points), and were capable of providing informed consent. Having a life expectancy of fewer than 6 months, serious impairments prior to the stroke that could have a significant impact on functional outcome or unstable medical condition after acute stroke were exclusion criteria.

**Measurements**

An experienced physiotherapist (MSc) with more than 9 years of experience from assessment and treatment of patients in an acute stroke unit conducted all assessments. The severity of stroke was scored using the SSS (Askim, Bernhardt, Churilov, and Indredavik, 2016). Activities of daily living (ADL) score were measured with the Barthel Index (Mahoney and Barthel, 1965) and degree of independence with the modified Rankin Scale (mRS) (van Swieten et al., 1988), in order to describe the functional level of the sample and make it possible to be comparable to the general stroke population and other study samples.

Gait was assessed using either a 6.10 m or a 5.49 m GAITRite® mat (CIR systems Inc. Franklin, NJ, USA). To measure gait asymmetry, the ratio between left and right foot was calculated for both step length and single support time. Walk ratio was calculated as the ratio between step length/cadence. Participants were instructed to walk back and forth at a self-selected gait speed, along the walkway which included 1 m at either end for acceleration/deceleration. Walking aids, such as a cane or a walker, were permitted only when necessary for safety reasons. The GAITRite mat has previously shown to be both valid (Bilney, Morris, and Webster, 2003) and reliable (Menz et al., 2004; Webster, Wittwer, and Feller, 2005) for assessing gait.

Berg Balance Scale (BBS) was applied in accordance with the tests manual guide (Berg, Wood-Dauphinee, Williams, and Gayton, 1989) to assess balance. The scale ranges from zero (worst) to 56 (normal balance) points and has been shown to be a reliable and valid measure of balance after stroke (Berg, Wood-Dauphinee, Williams, and Maki, 1992). A change of six points on the BBS is considered the minimal important change (MIC) early after stroke (Saso, Moe-Nilsen, Gunnes, and Askim, 2016).

The 6-minute walk test (6MWT) was used to assess walking capacity using a 20 m track following a standard protocol (Guyatt et al., 1985) where participants were instructed to walk as far as they could in 6 minutes. They were permitted to take a break during the test but informed that the timer would still be running. After each minute, participants were informed of the time remaining. The need for walking aid during testing was a joint decision between participant and physiotherapist and was only for safety. The 6MWT is a widely accepted method for measuring walking capacity (Butland et al., 1982), with a minimal clinically important change between 14.0 m and 30.5 m for adults with pathology (Bohannon and Crouch, 2017).

**Data and statistical analysis**

Data from the GAITRite mat were processed in the PKMAS® (version 5.07c2) (Egerton, Thingstad, and Helbostad, 2014) and transferred to Microsoft Excel 2016 and IBM SPSS Statistics version 25 for analysis. Demographic data were reported as mean values and standard deviation (SD) for all participants unless otherwise stated. Residuals were visually inspected for normal distribution by Q–Q plots and variables transformed if residuals were not normally distributed. Asymmetry was calculated as the percentage of the logarithm (LN) between the left (L)/right (R) leg (100x( LN(L)/LN(R)) ) providing a measure of percentage of asymmetry (Yogev et al., 2007). An average of the spatiotemporal gait parameters from the two walks was calculated. Paired sample t-tests were applied to investigate changes over 3 months in spatiotemporal gait parameters, walking capacity, and balance. Those showing a statistically significant change were applied in bivariate and multiple regression analyses for associations between changes in spatiotemporal gait parameters and changes in either of 6MWT and BBS. Because spatiotemporal gait parameters may influence each other, we set cutoff values for correlations between the parameters at below 0.9 and variance inflation factors
(VIF) >10 for inclusion in the multivariate analysis to avoid collinearity. Therefore, only gait speed, percentage of time in single support, walk ratio, and asymmetry measures were included in the multivariate analysis.

**Results**

A total of 98 people met the inclusion criteria and were recruited for the study. By 3 months, ten had declined further participation, eight were re-hospitalized and not available, and one participant was lost to follow-up due to technical error. Seventy-nine people (44 men, 55.7%) were therefore included in the final analysis. Table 1 shows demographic and functional data at baseline. Participants were discharged either to a rehabilitation center (n = 24, 30.4%) or home (n = 55, 69.6%) in accordance with their physical and cognitive level. At baseline, fourteen participants used a walker, six participants used a cane or a unilateral crutch, and one participant used bilateral crutches (Table 1). After 3 months, only three participants were still in need of a walker, four participants used a stick or unilateral crutch, and one participant used bilateral crutches.

**Table 1.** Demographic and functional data at baseline (n = 79). Mean (SD) unless otherwise stated.

|                       | Mean (SD) |
|-----------------------|-----------|
| Age (years)           | 75.4 (8.48) |
| Days hospitalized     | 6.5 (3.3) |
| Male gender, N (%)    | 44 (55.7) |
| Types of stroke       |           |
| Embolic stroke, N (%) | 75 (94.9) |
| Hemorrhagic stroke, N %| 4 (5.1) |
| Modified Rankin Scale (0–6) | 2.7 (1.0) |
| Barthel index (0–100) | 85.7 (14.8) |
| Scandinavian Stroke Scale (0–58) | 51.8 (4.6) |
| Bergs Balance Scale (0–56) | 37.7 (15.5) |
| 6-minute walk test (meters) | 400.9 (177.8) |
| Walking aid at baseline tests | 58 (73.4) |
| None, N (%)           | 7 (8.9) |
| Cane, N (%)           | 14 (17.7) |
| Walker, N (%)         |           |
| SD: Standard Deviation|           |

Table 2 shows changes in spatiotemporal gait parameters, balance, and walking capacity from the acute phase to 3 months later at self-selected gait speed. Participants increased their gait speed by 18% (0.2 m s⁻¹, p < .001), with 11% longer steps (6.6 cm, p < .001), spent 1.2% longer time in single support (p < .001), and increased their cadence by 7% (7.7 steps/min, p < .001). Walk ratio improved by 3% from 0.58 to 0.60 (p = .010). Both asymmetry measures indicated a decreased asymmetry after 3 months, but only step length asymmetry showed a statistically significant decrease (2.5%, p = .004). There was a statistically and clinically significant improvement in both balance (10.3 points, p < .001) and walking capacity (61 m, p < .001).

**Table 2.** Changes in spatiotemporal gait parameters, balance, and walking capacity from the acute phase to 3 months later at self-selected gait speed.

|                       | Baseline Mean (SD) | 3 months Mean (SD) | Mean change Mean (95% CI) | p-value |
|-----------------------|--------------------|--------------------|-------------------------|---------|
| Gait speed (m s⁻¹)    | 0.9 (0.3)          | 1.1 (0.3)          | 0.2 (0.1, 0.2)          | <.0001  |
| Step length (cm)      | 55.7 (12.9)        | 62.3 (13.1)        | 6.6 (4.5, 8.6)          | <.0001  |
| Stride width (cm)     | 8.1 (3.1)          | 7.6 (3.5)          | −0.5 (−1.2, 0.2)        | 0.129   |
| Single support (%)    | 33.9 (3.6)         | 35.1 (3.0)         | 1.2 (0.5, 1.8)          | <.0001  |
| Cadence (steps/min)   | 96.5 (16.7)        | 104.2 (12.0)       | 7.7 (5.0, 10.4)         | <.0001  |
| Walk ratio (step length/cadence) | 0.58 (0.11) | 0.60 (0.11)        | 0.02 (0.01, 0.03)       | 0.010   |
| Asymmetry step length (%) | 7.4 (3.9) | 4.9 (4.1)          | −2.5 (−4.1, −0.8)       | 0.004   |
| Asymmetry single support (%) | 5.9 (6.5) | 4.8 (4.7)          | −1.1 (2.4, −0.2)        | 0.098   |
| Bergs Balance Scale (range 0–56) | 37.7 (15.8) | 48.0 (10.0)        | 10.3 (7.9, 12.6)        | <.0001  |
| 6MWT (m)              | 380 (133)          | 441 (143)          | 61 (41, 79)             | <.0001  |

SD: Standard Deviation, CI: Confidence Interval, 6MWT: 6-Minute Walk Trial; p-value <.05.
measured by the 6MWT. The analysis showed a statistically significant association between increased walking distance and step length (i.e. 6.8 m increase for every extra centimeter of step length). This was also the case for cadence, where an increase in 5.1 m in 6MWT for an increase in cadence of one step/minute. For percentage of time in single support, a 1% improvement was associated with an increased walking capacity of 17.4 m. There was an increase in walking capacity with decreasing spatial and temporal asymmetry, with associations being statistically significant. Controlling for changes in all included spatiotemporal gait parameters, the multivariate analysis showed an increase in walking distance of 25.6 m for every 0.1 m s\(^{-1}\) increase in gait speed (95% CI 17.3 to 34.0, \(p < .001\)). The increase in gait speed accounted for 72% of the variation in change of walking capacity and the multivariate analysis had an \(R^2\) of 0.56.

### Discussion

Our results support clinically meaningful improvements in gait, balance, and walking capacity during the first 3 months after stroke. Improvements in step length, cadence, gait speed, percentage of time in single support, and step length asymmetry were all associated with the improvement in balance. Improvements in step length, cadence, gait speed, percentage of time in single support, walk ratio, and step length asymmetry measures were associated with the improvement in walking capacity. However, in the multivariate analysis, only change in gait speed was significantly associated with the changes in balance or walking capacity.

Improvements in many of the spatiotemporal gait parameters are thought to enable safer and more efficient gait. The improved gait speed of 0.2 m s\(^{-1}\) is considered clinically significant early after stroke (Fulk et al., 2011; Perera, Mody, Woodman, and Studenski, 2006; Tilson et al., 2010) and a gait speed above 0.8–1.0 m s\(^{-1}\) is considered safe in community ambulation. (Studenski et al., 2003). The increased step length and percent of time in single support are suggestive of an improvement in motor control with less time needed in double support (Kollen et al., 2005; Kwakkel, Kollen, and Twisk, 2006). Our results showing decreased step length asymmetry are in accordance with our hypothesis as we expected that early motor recovery would decrease asymmetry. However, single support asymmetry did not change significantly, possibly because it is slower to improve (Rozanski et al., 2019). The increased walk ratio in our study may suggest a more efficient gait, with the ratio moving toward the level of healthy adults (Sekiya and Nagasaki, 1998). The lack of improvement in single support asymmetry and the sustaining associations in multivariate analyses between gait speed and balance and walking capacity raises a question whether our findings are due to compensatory strategies. However, most of the other spatiotemporal gait parameters improve and are associated with both improved balance and walking capacity. Gait speed may be considered as the sum of spatiotemporal gait parameters.

### Table 3.

Bivariate and multivariate associations between changes in spatiotemporal gait parameters and changes in balance from acute phase to 3 months later.

| Bivariate analysis | Multivariate analysis |
|--------------------|-----------------------|
| **Coefficient (95% CI)** | **Standardized coefficient** | **p-value** | **Coefficient (95% CI)** | **Standardized coefficient** | **p-value** |
| Step length (cm) | 0.5 (0.3, 0.8) | 0.4 | <0.001 | 13.8 (0.5, 27.8) | 0.3 | 0.042 |
| Cadence (steps/min) | 0.3 (0.2, 0.5) | 0.4 | 0.001 | 0.3 (−1.0, 1.5) | 0.1 | 0.684 |
| Gait speed (m s\(^{-1}\)) | 18.1 (8.3, 27.8) | 0.4 | <0.001 | 11.1 (−27.8, 50.0) | 0.1 | 0.572 |
| Single support (%) | 1.3 (0.5, 2.1) | 0.3 | 0.003 | −0.2 (−0.6, 0.2) | −0.1 | 0.354 |
| Walk ratio (step length/cadence) | 22.4 (−17.6, 62.3) | 0.1 | 0.268 | −0.2 (−0.7, −0.1) | −0.2 | 0.036 |
| Asymmetry step length (%) | −0.3 (−0.7, −0.1) | −0.2 | 0.036 | −0.2 (−0.6, 0.2) | −0.1 | 0.354 |

CI: Confidence Interval; \(p\)-value < 0.05.

### Table 4.

Bivariate and multivariate associations between changes in spatiotemporal gait parameters change in walking capacity from acute phase to 3 months later.

| Bivariate analysis | Multivariate analysis |
|--------------------|-----------------------|
| **Coefficient (95% CI)** | **Standardized coefficient** | **p-value** | **Coefficient (95% CI)** | **Standardized coefficient** | **p-value** |
| Step length (cm) | 6.8 (5.2, 8.3) | 0.7 | <0.001 | 256 (173, 340) | 0.7 | <0.001 |
| Cadence (steps/min) | 5.1 (3.7, 6.5) | 0.7 | <0.001 | 1.0 (−6.8, 8.8) | <0.1 | 0.792 |
| Gait speed (m s\(^{-1}\)) | 265 (209, 322) | 0.7 | <0.001 | −49.9 (−311.5, 211.6) | <0.1 | 0.705 |
| Single support (%) | 17.4 (11.1, 23.7) | 0.6 | <0.001 | −0.8 (−3.9, 2.4) | <0.1 | 0.619 |
| Walk ratio (step length/cadence) | 349.8 (16.4, 698.1) | 0.2 | 0.049 | −5.1 (−8.9, −1.4) | −0.3 | 0.008 |
| Asymmetry step length (%) | −5.1 (−8.9, −1.4) | −0.3 | 0.008 | −0.8 (−3.9, 2.4) | <0.1 | 0.619 |

CI: Confidence Interval; \(p\)-value < 0.05.
and may have affected associations between other spatiotemporal gait parameters and balance and walking capacity. We would, therefore, argue that the results found here represent an improvement toward a safer and more efficient gait. It is possible that some participants improve because of compensatory strategies whereas others improvement is due to an improved gait. This aspect could be interesting to study in future studies.

The bivariate analysis shows several associations between changes in spatiotemporal gait parameters and changes in balance. A higher percentage of time in single support on the affected side allows for a longer swing phase of the unaffected leg and would help achieve longer steps. These improvements are also likely to be reflected in the spatial (step length) asymmetry measure (Lewek, Bradley, Wutzke, and Zinder, 2014). There was an association between decreased step length asymmetry and improved balance, suggesting that balance improves as step length asymmetry decreases. When including all gait parameters in the multivariate analysis, most associations disappeared apart from the association between gait speed and balance. Gait speed may therefore effectively be the “sum” of all the other gait parameters (Brandstater, de Bruin, Gowland, and Clark, 1983; Roth et al., 1997; Wonsetler and Bowden, 2017). We hypothesized improved step length would be associated with improved balance. However, because our model breached limits of collinearity, step length was excluded from the multiple analysis. The low $R^2$ value of 0.17 in the multiple regression model suggests that there are other factors explaining more of the changes in balance. Gait and balance are both complex tasks that rely on the functioning of multiple systems, such as improved vestibular function (Tramontano et al., 2018); improved postural stability (Puckree and Naidoo, 2014); and improved muscle strength (Lund et al., 2018), and it is likely that these systems also can be associated with changes in balance.

The bivariate analysis showed that improvements in several spatiotemporal gait parameters were associated with improved walking capacity. The improvements in spatiotemporal gait parameters are likely to lead to a more efficient gait, with a decreased energy expenditure during walking (Awad et al., 2015; Bae et al., 2018; Farris, Hampton, Lewek, and Sawicki, 2015). It has also previously been shown that walking distance achieved during prolonged walks, such as the 6MWT, is strongly associated with gait speed (Awad et al., 2015). Results from our multivariate analysis show that only changes in gait speed sustained associated with increased walking capacity when including all the variables. This suggests that they were not independently associated with 6MWT when gait speed is also included in the model. The multivariate analyses excluded step length and cadence because of collinearity. However, without breaking the limits, there seems to be collinearity between speed and the other measures that were included in the model. The model had an $R^2$ of 0.56, showing that improvements in speed over a short 10 m walkway are reflected in improvements in speed over longer distances.

There are some methodological limitations to consider in this study. Our inclusion criteria of being able to walk 10 m without personal assistance will have excluded participants with severe physical impairments from the stroke. The baseline mRS of 2.7, the relatively high BI of 85.7, and a gait speed at baseline close to 1.0 m s$^{-1}$ all suggest that participants were only mildly to moderately affected by the stroke. However, the relatively large standard deviations for both spatiotemporal gait parameters, balance, and walking capacity suggest a heterogeneous group of participants within this mobile cohort. Our results are also in line with data from the Norwegian Stroke Registry from 2017, showing comparable results for stroke severity, functional impairment, and independence in ADL (Norwegian Directorate of Health, 2017).

Participants were permitted to use a walking aid, if necessary, for safety, when walking unassisted on the GAITRite mat and during the 6MWT. The need for a walking aid could be expected to change from the acute phase to 3 months later for several participants. It is likely that the use of a walking aid could influence both gait speed, asymmetry, and efficiency and could question the reliability of the walking tests. The first 3 months after stroke is the period with most spontaneous recovery takes place and it is therefore likely that the need for a walking aid changed. Because we wanted to include a representative group of participants, we chose to include participants in need of a walking aid in the acute phase. This could, however, represent a possibly measurement bias of our results. Therefore, we tested the bivariate and multivariate analysis when excluding those in need of a walking aid at baseline (n = 58). In both analyses, all coefficients pointed in the same direction between improved spatiotemporal gait parameters and improved balance, but improved gait speed was no longer associated with improved balance in the multivariate analysis. This was also the case between improved gait speed and improved walking capacity, with a borderline significance level ($p = .060$) in the multivariate analysis. The lack of associations is possibly caused by the smaller sample size. However, single support asymmetry changed from a non-significant association to a significant association of $-5.60 \text{ m} (-10.25$ to 0.94, $p = .020$) with changes in walking capacity. A possible explanation for this change of direction for the coefficient is that the walking aid helped maintain postural stability and therefore masked...
associations. The post hoc analyses were conducted to control whether the results were affected using walking aids. However, excluding participants in need of walking aids did not change our results.

The BBS is a common, reliable, and valid measure of balance after stroke (Berg, Wood-Dauphinee, Williams, and Maki, 1992). However, most tasks in the BBS are of standing balance. With balance control during gait requiring the ability to adjust relative to the surroundings (Zou et al., 2018) there is a question whether BBS is task-specific enough to capture balance during walking. A measure of balance during walking might have shown different results.

The change of GAITRite mats was done because of an error with the first mat. The only difference between the mats was their length. Although the length of the mat could lead to more steps, we do not expect the change of GAITRite mats to threaten the overall reliability of the study.

Clinical implications

Results from this study show that changes in spatiotemporal gait parameters are associated with changes in both balance and walking capacity over the first 3 months after stroke. Changes in gait speed may be considered as a "sum" of the changes across several gait parameters and is an easy and low-cost parameter to measure. Therefore, assessing gait speed may be helpful when monitoring the safety and efficiency of gait after stroke.

Conclusion

The observed spatiotemporal gait parameters improved from the acute phase to 3 months later. Most were associated with improved balance and walking capacity. The associations suggest that improvements in spatiotemporal gait parameters can reveal the safety and efficiency of gait. The analysis shows that improved spatiotemporal gait parameters do explain improved walking capacity better than improved balance.

Acknowledgments

We would like to thank the Department of Stroke for collaboration throughout the project and the patients and their families who agreed to participate in our study.

Disclosure statement

The authors report no conflict of interest.

References

Askim T, Bernhardt J, Churilov L, Indredavik B 2016 The Scandinavian stroke scale is equally as good as the national institutes of health stroke scale in identifying 3-month outcome. Journal of Rehabilitation Medicine 48: 909–912. doi: 10.2340/16501977-2155

Awad LN, Palmer JA, Pohlig RT, Binder-Macleod SA, Reisman DS 2015 Walking speed and step length asymmetry modify the energy cost of walking after stroke. Neurorehabilitation and Neural Repair 29: 416–423.

Bae J, Awad LN, Long A, O’Donnell K, Hendron K, Holt KG, Ellis TD, Walsh CJ 2018 Biomechanical mechanisms underlying exosuit-induced improvements in walking economy after stroke. Journal Experimental Biology 221: jeb168815.

Berg KO, Wood-Dauphinee S, Williams JJ, Gayton D 1989 Measuring balance in the elderly: Preliminary development of an instrument. Physiotherapy Canada 41: 304–311.

Berg KO, Wood-Dauphinee SL, Williams JJ, Maki B 1992 Measuring balance in the elderly: Validation of an instrument. Canadian Journal of Public Health 83: 7–11.

Bilney B, Morris M, Webster K 2003 Concurrent related validity of the GAITRite walkway system for quantification of the spatial and temporal parameters of gait. Gait and Posture 17: 68–74.

Bohannon RW, Andrews A, Smith M 1988 Rehabilitation goals of patients with hemiplegia. International Journal of Rehabilitation Research 11: 181–184.

Bohannon RW, Crouch R 2017 Minimal clinically important difference for change in 6-minute walk test distance of adults with pathology: A systematic review. Journal of Evaluation in Clinical Practice 23: 377–381.

Brandstater ME, de Bruin H, Gowland C, Clark BM 1983 Hemiplegic gait: Analysis of temporal variables. Archives of Physical Medicine and Rehabilitation 64: 583–587.

Butland RJ, Pang J, Gross ER, Woodcock AA, Geddes DM 1982 Two-, six-, and 12-minute walking tests in respiratory disease. British Medical Journal 284: 1607–1608.

Cruz TH, Lewek MD, Dhaffer YY 2009 Biomechanical impairments and gait adaptations post-stroke: Multi-factorial associations. Journal of Biomechanics 42: 1673–1677.

Cummings SR, Studenski S, Ferrucci L 2014 A diagnosis of dismobility - Giving mobility clinical visibility: A mobility working group recommendation. JAMA 311: 2061–2062.

Dobkin BH, Nadeau SE, Behrman AL, Wu SS, Rose DK, Bowden M, Studenski S, Lu X, Duncan PW 2014 Prediction of responders for outcome measures of locomotor experience applied post stroke trial. Journal of Rehabilitation Research and Development 51: 39–50.

Duncan PW, Sullivan KJ, Behrman AL, Azen SP, Wu SS, Nadeau SE, Dobkin BH, Rose DK, Tilson JK 2007 Protocol for the Locomotor Experience Applied Post-stroke (LEAPS) trial: A randomized controlled trial. BMC Neurology 7: 39.

Egerton T, Danoudis M, Huxham F, Iansek R 2011 Central gait control mechanisms and the stride length - Cadence relationship. Gait and Posture 34: 178–182.
Egerton T, Thingstad P, Helbostad JL 2014 Comparison of programs for determining temporal-spatial gait variables from instrumented walkway data: PKmas versus GAITRite. BMC Research Notes 7: 542.

Farris DJ, Hampton A, Lewek MD, Sawicki GS 2015 Revisiting the mechanics and energetics of walking in individuals with chronic hemiparesis following stroke: From individual limbs to lower limb joints. Journal of Neuroengineering and Rehabilitation 12: 24.

Forrester LW, Roy A, Krywonis A, Kehs G, Krebs HI, Macko RF 2014 Modular ankle robotics training in early subacute stroke: A randomized controlled pilot study. Neurorehabilitation and Neural Repair 28: 678–687.

Fulk GD, He Y, Boyle P, Dunning K 2017 Predicting home and community walking activity poststroke. Stroke 48: 406–411.

Fulk GD, Ludwieg M, Dunning K, Golden S, Boyle P, West T 2011 Estimating clinically important change in gait speed in people with stroke undergoing outpatient rehabilitation. Journal of Neurologic Physical Therapy 35: 82–89.

Guyatt GH, Sullivan MJ, Thompson PJ, Fallen EL, Pugsley SO, Taylor DW, Berman LB 1985 The 6-minute walk: A new measure of exercise capacity in patients with chronic heart failure. Canadian Medical Association Journal 132: 919–923.

Hendrickson J, Patterson KK, Inness EL, McIlroy WE, Mansfield A 2014 Relationship between asymmetry of quiet standing balance control and walking post-stroke. Gait and Posture 39: 177–181.

Jorgensen HS, Nakayama H, Raaschou HO, Vive-Larsen J, Stoier M, Olsen TS 1995 Outcome and time course of recovery in stroke. Part I: outcome. The Copenhagen stroke study. Archives of Physical Medicine and Rehabilitation 76: 399–405.

Kollen B, van de Port I, Lindeman E, Twisk J, Kwakkel G 2005 Predicting improvement in gait after stroke: A longitudinal prospective study. Stroke 36: 2676–2680.

Kwakkel G, Kollen B, Twisk J 2006 Impact of time on improvement of outcome after stroke. Stroke 37: 2348–2353.

Lee IH 2015 Does the speed of the treadmill influence the training effect in people learning to walk after stroke? A double-blind randomized controlled trial. Clinical Rehabilitation 29: 269–276.

Lewek MD, Bradley CE, Wutzke CJ, Zinder SM 2014 The relationship between spatiotemporal gait asymmetry and balance in individuals with chronic stroke. Journal of Applied Biomechanics 30: 31–36.

Lord SE, McPherson K, McNaughton HK, Rochester L, Weatherall M 2004 Community ambulation after stroke: How important and obtainable is it and what measures appear predictive? Archives of Physical Medicine and Rehabilitation 85: 234–239.

Lund C, Dalgas U, Gronborg TK, Andersen H, Severinsen K, Riemenschneider M, Overgaard K 2018 Balance and walking performance are improved after resistance and aerobic training in persons with chronic stroke. Disability and Rehabilitation 40: 2408–2415.

Mahoney FI, Barthel DW 1965 Functional evaluation: The Barthel index. Maryland State Medical Journal 14: 61–65.

Menz HB, Latt MD, Tiedemann A, Kwan MS, Lord SR 2004 Reliability of the GAITRite walkway system for the quantification of temporo-spatial parameters of gait in young and older people. Gait and Posture 20: 20–25.

Michael KM, Allen JK, Macko RF 2006 Fatigue after stroke: Relationship to mobility, fitness, ambulatory activity, social support, and falls efficacy. Rehabilitation Nursing 31: 210–217.

Mizuike C, Ohgi S, Morita S 2009 Analysis of stroke patient walking dynamics using a tri-axial accelerometer. Gait and Posture 30: 60–64.

Nadeau S, Betschart M, Bethoux F 2013 Gait analysis for poststroke rehabilitation: The relevance of biomechanical analysis and the impact of gait speed. Physical Medicine and Rehabilitation Clinics of North America 24: 265–276.

Norwegian Directorate of Health 2017 Annual report. Norwegian Directorate of Health. Oslo, Norway. https://www.helsidirektoratet.no/retningslinjer/hjerneslag.

Olney SJ, Richards C 1996 Hemiparetic gait following stroke. Part I: Characteristics. Gait and Posture 4: 136–148.

Patterson KK, Gage WH, Brooks D, Black SE, McIlroy WE 2010 Evaluation of gait symmetry after stroke: A comparison of current methods and recommendations for standardization. Gait and Posture 31: 241–246.

Patterson KK, Mansfield A, Biasin L, Brunton K, Inness EL, McIlroy WE 2015 Longitudinal changes in poststroke spatiotemporal gait asymmetry over inpatient rehabilitation. Neurorehabilitation and Neural Repair 29: 153–162.

Perera S, Mody SH, Woodman RC, Studenski SA 2006 Meaningful change and responsiveness in common physical performance measures in older adults. Journal of American Geriatric Society 54: 743–749.

Puckree T, Naidoo P 2014 Balance and stability-focused exercise program improves stability and balance in patients after acute stroke in a resource-poor setting. PM&R 6: 1081–1087.

Rose DK, DeMark L, Fox EJ, Clark DJ, Wludzyka P 2018 A backward walking training program to improve balance and mobility in acute stroke: A pilot randomized controlled trial. Journal of Neurologic Physical Therapy 42: 12–21.

Roth EJ, Merbitz C, Mroczek K, Dugan SA, Suh WW 1997 Hemiplegic gait. Relationships between walking speed and other temporal parameters. American Journal of Physical Medicine and Rehabilitation 76: 128–133.

Rozanski GM, Wong JS, Inness EL, Patterson KK, Mansfield A 2019 Longitudinal change in spatiotemporal gait symmetry after discharge from inpatient stroke rehabilitation. Disability and Rehabilitation 42: 705–711.

Saso A, Moe-Nilsen R, Gunnnes M, Askim T 2016 Responsiveness of the berg balance scale in patients early after stroke. Physiotherapy Theory and Practice 32: 251–261.

Sekiya N, Nagasaki H 1998 Reproducibility of the walking patterns of normal young adults: Test-retest reliability of the walk ratio (step-length/step-rate). Gait and Posture 7: 225–227.

Stenhagen M, Ekstrom H, Nordell E, Elmstahl S 2014 Accidental falls, health-related quality of life and life satisfaction: A prospective study of the general elderly population. Archives of Gerontology and Geriatrics 58: 95–100.

Studenski S, Perera S, Wallace D, Chandler JM, Duncan PW, Rooney E, Fox M, Guralnik JM 2003 Physical performance measures in the clinical setting. Journal of the American Geriatric Society 51: 314–322.
van Tramontano M, Bergamini E, Iosa M, Belluscio V, Vannozzi G, Morone G 2018 Vestibular rehabilitation training in patients with subacute stroke: A preliminary randomized controlled trial. NeuroRehabilitation 43: 247–254.

van de Port IG, Kwakkel G, Lindeman E 2008 Community ambulation in patients with chronic stroke: How is it related to gait speed? Journal of Rehabilitation Medicine 40: 23–27.

van Dijk MM, Meyer S, Sandstad S, Wiskerke E, Thuiwis R, Vandekerckhove C, Myny C, Ghosh N, Beyens H, Dejaeger E, et al. 2017 A cross-sectional study comparing lateral and diagonal maximum weight shift in people with stroke and healthy controls and the correlation with balance, gait and fear of falling. PloS One 12: e0183020.

van Ooijen MW, Heeren A, Smulders K, Geurts AC, Janssen TW, Beek PJ, Weerdesteyn V, Roerdink M 2015 Improved gait adjustments after gait adaptability training are associated with reduced attentional demands in persons with stroke. Experimental Brain Research 233: 1007–1018.

van Swieten JC, Koudstaal PJ, Visser MC, Schouten HJ, van Gijn J 1988 Interobserver agreement for the assessment of handicap in stroke patients. Stroke 19: 604–607.

Verma R, Arya KN, Garg RK, Singh T 2011 Task-oriented circuit class training program with motor imagery for gait rehabilitation in poststroke patients: A randomized controlled trial. Topics in Stroke Rehabilitation 18: 620–632.

evon Schroeder HP, Coutts RD, Lyden PD, Billings E, Nickel VL 1995 Gait parameters following stroke: A practical assessment. Journal of Rehabilitation Research and Development 32: 25–31.

Webster KE, Wittwer JE, Feller JA 2005 Validity of the GAITRite walkway system for the measurement of averaged and individual step parameters of gait. Gait and Posture 22: 317–321.

Weerdesteyn V, de Niet M, van Duijnhoien HJ, Geurts AC 2008 Falls in individuals with stroke. Journal of Rehabilitation Research and Development 45: 1195–1213.

Wonsetler EC, Bowden MG 2017 A systematic review of mechanisms of gait speed change post-stroke. Part 1: Spatiotemporal parameters and asymmetry ratios. Topics In Rehabilitation Science 24: 435–446.

Yoge G, Plotnik M, Peretz C, Giladi N, Hausdorff JM 2007 Gait asymmetry in patients with Parkinson’s disease and elderly fallers: When does the bilateral coordination of gait require attention? Experimental Brain Research 177: 336–346.

Zou L, Sasaki JE, Zeng N, Wang C, Sun L 2018 A systematic review with meta-analysis of mindful exercises on rehabilitative outcomes among poststroke patients. Archives of Physical Medicine and Rehabilitation 99: 2355–2364.