Sensory Impairments of the Lower Limb after Stroke: A Pooled Analysis of Individual Patient Data

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Objective: To obtain more generalizable information on the frequency and factors influencing sensory impairment after stroke and their relationship to mobility and function. **Method:** A pooled analysis of individual data of stroke survivors ($N = 459$); mean (SD) age = 67.2 (14.8) years, 54% male, mean (SD) time since stroke = 22.33 (63.1) days, 50% left-sided weakness. Where different measurement tools were used, data were recoded. Descriptive statistics described frequency of sensory impairments, kappa coefficients investigated relationships between sensory modalities, binary logistic regression explored the factors influencing sensory impairments, and linear regression assessed the impact of sensory impairments on activity limitations. **Results:** Most patients' sensation was intact (55%), and individual sensory modalities were highly associated ($\kappa = 0.60$, $P < .001$). Weakness and neglect influenced sensory impairment ($P < .001$), but demographics, stroke pathology, and spasticity did not. Sensation influenced independence in activities of daily living, mobility, and balance but less strongly than weakness. **Conclusions:** Pooled individual data analysis showed sensation of the lower limb is grossly preserved in most stroke survivors but, when present, it affects function. Sensory modalities are highly interrelated; interventions that treat the motor system during functional tasks may be as effective at treating the sensory system as sensory retraining alone.

Key words: *balance, mobility, proprioception, recovery, sensation, stroke, tactile*

Sensory impairments after stroke are frequently reported (between 11% and 60%) and are closely related to recovery of function.[1-5] Stroke survivors with impaired sensation, hemianopia, and balance problems[6-8] have a higher than normal incidence of falls and tend to make less functional recovery than those with motor impairments alone.[9-11] Stimulation of the sensory system is part of many stroke therapy treatment programs[12,13] because of the belief that intact sensation is a requirement for effective movement and function.[14,15] Despite the clinical importance of sensory loss after stroke, it has received relatively little research attention compared with motor or cognitive impairments. Furthermore, it is rarely included as a factor in epidemiological studies of recovery or activity limitations. Several studies have included assessment of sensory loss, but they have often recruited highly selected populations or used different methods of sensory evaluation.[3,6,7,16-20] To date, attempts to evaluate the nature and impact of sensory loss after stroke[21-23] have been limited by small sample sizes and the lack of a gold standard for sensory evaluation. Consequently, we undertook a pooled analysis of data from 5 centers to describe the frequency of sensory impairments, investigate factors that influence sensory impairments, and explore the influence of sensory impairments on functional activity. This article concerns sensory impairments of the lower limb; the upper limb will be reported separately.

Method

We searched the literature to identify studies with a described sensory loss of the lower limb after stroke using standardized sensory measurement tools with published evidence of their psychometric properties. We contacted the authors

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Table 1. The recruitment criteria for the included studies

	Salford (Tyson et al[21]) N = 251	**Oxford (Windward et al[23]) N = 100**	**Nottingham (Connell et al[22]) N = 70**	**Adelaide (Lynch et al[25]) N = 21**	**Erasmus (Stolk-Hornsveld et al[24]) N = 17**
Recruitment location and strategy	RASP: consecutive admissions to stroke services in Salford POET: stroke and rehabilitation services and support groups across northwest England	Consecutive admissions to the stroke services in 4 hospitals in southern England and the Oxford Stroke Register	Consecutive admission to 2 stroke rehabilitation units in Nottingham	Inpatients in rehabilitation center in Adelaide	Consecutive admissions to Erasmus Medical Center University Hospital Rotterdam
Time since stroke when recruited	RASP: 2-4 weeks poststroke POET: any time	Any time	On admission to rehabilitation unit	Any time	Any time
First-time stroke only?	RASP: yes POET: no	Yes	Yes	Yes	No
Limits to premorbid activity or other conditions	Previously able to walk independently and no other conditions limiting mobility	No other neurological conditions or impairments preventing participation	No other neurological impairments or significant premorbid disability	No preexisting sensory deficits or severely limited mobility	No other neurological conditions or impairments preventing participation

Note: POET = Postural Objective Evaluation Tool; RASP = Rivermead Assessment of Somatosensory Perception.

to request access to their data. Seven authors were identified; 5 (the authors of the current article) had data available and were included in this study.[21-25] The recruitment criteria for the included studies were broadly similar and are detailed in **Table 1**.

One study (the Postural Objective Evaluation Tool [POET] from Salford, UK) was previously unpublished. Thus, the data from Salford included 2 studies: POET (N = 149) and the Rivermead Assessment of Somatosensory Perception study[21] (N = 102) combined. The following standardized sensory assessment tools were used:

- Erasmus modified Nottingham Sensory Assessment[24] (Erasmus study; N = 17)
- Siemmes-Weinstein filaments[26] and distal proprioception test[27] (Adelaide study; N = 21)
- Nottingham Sensory Assessment[28] (Nottingham study; N = 70)
- Rivermead Assessment of Somatosensory Performance[29] (Oxford study, N = 100; and Salford studies, N = 251)

Research ethics approval was obtained for the original studies but not for this secondary analysis. All the data used were anonymized. Raw data were collated by the lead author, and data were extracted and recoded as detailed below. Data extraction and coding was independently verified by 2 authors (J.L.C. and L.C.). For the pooled analysis, data for 2 sensory modalities (touch and proprioception) were extracted and analyzed with regard to 2 subcomponents: detection and discrimination. In total, there are 4 defined areas:

- Tactile detection (n = 439): ability to detect light touch on dorsum of foot
- Tactile discrimination (n = 385): ability to locate light touch on dorsum of the foot
- Proprioception detection (n = 414): ability to detect movement at the ankle
- Proprioception discrimination (n = 435): ability to detect the direction of movement at the ankle

As different standardized measurement tools were used, raw data were recoded so the touch and proprioception modalities could be analyzed as absent, impaired, or intact (see **Appendix**) and further combined to obtain the following information:

- Tactile sensation (n = 383): tactile detection + discrimination scores

- Proprioception (n = 414): proprioception detection + discrimination scores
- Detection (n = 405): combined tactile + proprioception detection scores
- Discrimination (n = 377): combined tactile + proprioception discrimination scores
- Overall foot sensation (n = 443): all modalities combined

The other parameters measured were age, gender, and type of stroke (**Table 1**).

As various measures of mobility and balance were used across the studies, data were recoded to form clinically and functionally meaningful and important levels of ability: 3 categories for mobility (unable to walk, mobile with assistance, and independently mobile) and 4 categories for balance (very severe, severe, moderate, and mild). These categories were decided on by discussion among the authors. Further details of how the recoding was undertaken are found in the **Appendix**.

Descriptive statistics described the frequency of sensory impairments. Kappa coefficients and percentage agreement investigated the agreement between modalities, Spearman rank correlations estimated the correlation, and Cronbach's alpha assessed the internal consistency. Binary logistic regression explored the factors influencing sensory impairments, with overall foot sensation (present or absent/impaired) as the dependent variable. In all cases, the study identifier was entered as a covariate, and data were entered as independent variables to investigate the effects of the following:

- Demographic factors: a model was constructed with age, sex, and premorbid activity
- Stroke-related factors: type of stroke, time since stroke, and side of hemiplegia; there were 2 outlier values for time since stroke and the analysis was done both with and without the outliers
- Other stroke-related impairments: weakness, neglect, and lower limb spasticity

To investigate the impact of sensory impairments on activity limitations, we constructed linear regression models using the enter method with mobility, balance, and independence in activities of daily living (ADLs) as the dependent variables. For each model, stroke-related impairments and factors known to influence outcome (age and time since stroke) were entered as single independent variables. Subsequently, those showing a significant influence were entered into a multiple regression model (with mobility, balance, and independence in ADLs as the dependent variables and the significant stroke-related impairments and other factors as the independent variables). When the selected studies involved repeated measurements over time, only the data from the first assessment were included.

Results

Data for 459 participants were identified and pooled. Mean values were typical of other stroke rehabilitation studies, with equal numbers of men (54%) and women (46%), a mean age of 67.2 years, slightly more participants with left hemiplegia than right, and mainly ischemic stroke. Mean time since stroke was 22 days (SD = 63); however, this included outliers at 615 day and 963 days. If these values were removed, then mean time since stroke was 19 days (SD = 35.2 days; median = 8 days, interquartile range = 4-18.5). Most patients were recruited within the first 2 weeks of their stroke. Further details describing the sample are shown in **Table 2**.

Frequency of lower limb sensory impairments and the relationships between modalities

Most patients' lower limb sensation was intact (**Table 3**), both overall (55%) and when individual sensory modalities (61%-83%) were considered. More patients had intact proprioception than tactile sensation (76% vs 61%). Impairment of discrimination produced a similar frequency (37%) to detection (33%). For the single modalities, the frequency of complete absence was similar to that for impairment (10%-23% vs 8%-13%). Impairment was more frequent than absence when the combined modalities (proprioception, tactile sensation, detection, or discrimination) were considered (14%-27% vs 6%-11%), which is unsurprising given their compound nature.

The association between scores for all modalities was highly significant ($\kappa = 0.60$, $P < .001$; percentage agreement for intact scores = 84%, for impaired score = 68%, and for absent

Table 2. Description of participants in the included studies

	Salford (Tyson et al[21]) N = 251	**Oxford (Windward et al[23]) N = 100**	**Nottingham (Connell et al[22]) N = 70**	**Adelaide (Lynch et al[25]) N = 21**	**Erasmus (Stolk-Hornsveld et al[24]) N = 17**	**Total N = 459**
Mean (SD) age, years (N = 459)	68.6 (13.9)	64.1 (17.2)	71.3 (9.7)	61.4 (13.8)	52.9 (20.3)	67.2 (14.8)
Gender, M/F (N = 459)	132/119	53/47	36/34	16/5	8/9	192/167 (54%/46%)
Mean (SD) time since stroke, days (N = 459)	17.45 (76.7)	41.30 (55.4)	15.06 (8.7)	24.86 (10.1)	9.35 (5.2)	22.33 (63.1)
Type of stroke: ischemic/hemorrhage (N = 459)	89/13	48/8	59/8	18/3	12/4	226/36 (86%/14%)
Side of hemiplegia: left/right/both (N = 459)	131/115/5	50/50/0	42/28/0	14/7/0	9/8/0	230/224/5
Mean (SD) premorbid activity: modified Rankin (n = 172)	0.43 (0.8) Median = 0 IQR = 0-0		0.6 (0.8) Median = 0 IQR = 0-0			0.5 (0.8) Median = 0 IQR = 0-1
Mean (SD) lower limb weakness: Motricity Index (n = 353)	57.6 (30.3)	62.9 (32.7)			48.4 (43.8)	58.5 (31.6) Median = 61.5 IQR = 38-83
Mean (SD) balance, recoded (n = 450)	2.2 (1.1) Median = 2 IQR = 1-1	2.2 (1.2) Median = 1 IQR = 1-2	1.9 (1.5) Median = 1 IQR = 1-1	3.1 (0.8) Median = 3 IQR = 2-3	1.8 (1.2) Median = 1 IQR = 1-1	2.2 (1.2) Median = 2 IQR = 1-3
Mean (SD) mobility, recoded (N = 459)	1.7 (0.9) Median = 1 IQR = 1-2	1.6 (0.9) Median = 1 IQR = 1-1	1.4 (0.8) Median = 1 IQR = 1-1	2.7 (0.5) Median = 3 IQR = 2-3	1.6 (0.7) Median = 1 IQR = 1-1	1.7 (0.9) Median = 1 IQR = 1-3
Mean (SD) independence in ADLs, Barthel Index (n = 339)	11.3 (5.9) Median = 12 IQR = 6-12	12.1 (5.1) Median = 12 IQR = 9-16			12.0 (4.24) Median = 12 IQR = 6-12	11.5 (5.7) Median = 12 IQR = 7-17
Mean lower limb spasticity, Modified Ashworth Scale (n = 166)	0.3 (0.9) Median = 0 IRQ = 0-0				0.3 (0.7) Median = 0 IQR = 0-0	0.3 (0.9) Median = 0 IQR = 0-0
Neglect, No. with neglect; Star Cancellation Test < 44 (n = 321)	59 (24%)		28 (40%)			87 (27%)

Note: For ordinal scales, mean (and standard deviation) and the median (and interquartile range [IQR]) are included to aid any future meta-analysis and comparisons with other research reports. Blank cells indicate that the parameter was not measured. ADLs = activities of daily living.

Table 3. Frequency (and percentage) of sensory impairments after stroke

	Intact	**Impaired**	**Absent**
Overall sensation	244 (55%)	171 (39%)	28 (6%)
Tactile sensation	235 (61%)	105 (27%)	43 (11%)
Proprioception	317 (76%)	57 (14%)	40 (10%)
Detection	278 (67%)	101 (25%)	26 (6%)
Discrimination	238 (63%)	101 (27%)	38 (10%)
Tactile detection	308 (70%)	59 (13%)	72 (16%)
Tactile discrimination	260 (68%)	35 (9%)	90 (23%)
Proprioception detection	343 (83%)	31 (8%)	40 (10%)
Proprioception discrimination	335 (77%)	38 (9%)	62 (14%)

Note: Values given as n (%). Intact = all tests passed; impaired = some tests failed; absent = all tests failed.

scores = 95%), indicating that patients tended to score the same for all lower limb modalities. However, all combinations of passed and failed modalities were found, and few patients (n = 28; 6%) failed all modalities. This was echoed when the relationships between modalities were considered. Internal consistency between items was .95, indicating they were measuring a single construct. The correlations between individual modalities and overall sensation were strong (r = 0.61-0.92), and there was significant intercorrelation within the tactile and proprioceptive modalities (all scored $P < .001$; r = 0.46-0.98).

Factors influencing sensory loss

The binary logistic regression showed that none of the demographic variables (age, sex, premorbid activity) significantly affected sensory impairment (age, *P* = .34; sex, *P* = .35; premorbid activity, *P* = .88), nor were the stroke pathology variables significant (side of hemiplegia, *P* = .62; type of stroke, *P* = .06; time since stroke, *P* = .23). Of the stroke-related impairments, weakness (*P* < .001) and neglect (*P* < .001) had a significant influence on sensory impairment, but spasticity was not significant (*P* = .53).

Influence of sensation on function

All sensory modalities showed weak (*r* = 0.17-0.32) but significant (*P* < .001) correlations with ADLs, mobility, and balance, indicating that sensory loss was related to activity. Individual linear regression models showed that all factors (sensation, weakness, spasticity, and neglect) except spasticity (*P* = .13) were significant predictors of ADLs. The multiple regression produced a significant model (*P* < .001), accounting for 46% of variance, in which all factors emerged as an independently significant predictors of ADLs. Weakness was strongest (*P* < .001) followed by sensation and neglect (both *P* = .004). Further details are shown in **Table 4**. This was maintained if overall foot sensation was replaced with tactile sensation or proprioception.

All factors, except spasticity, significantly influenced mobility. So these were entered into a multiple regression, which produced a significant model (*P* = .00) accounting for 22% of variance. Only lower limb weakness emerged as an independently significant predictor of mobility (*P* < .001; sensation, *P* = .12; neglect, *P* = .11). Further details are shown in **Table 4**. Neither proprioception nor tactile sensation was independently significant if it replaced overall sensation in the model.

Similarly, all factors except spasticity (*P* = .13) significantly influenced balance. The multiple linear regression model with balance as the dependent variable accounted for 36% of variance, but only lower limb weakness emerged as an independently significant predictor of balance (*P* < .001; sensation and neglect both had *P* values of .07). Further details are shown in **Table 4**. When overall sensation was swapped for tactile sensation or proprioception, neither was independently significant.

Discussion

The results of this study show that for most stroke survivors, sensation in the foot is preserved. Only 6% of patients have a complete absence

Table 4. Results of multiple regression of the factors influencing independence in activities of daily living, mobility, and balance

Dependent variable	Standardized beta coefficients	*t*	*P* value	95% confidence interval
Activities of daily living				
(Constant)		7.531	.000	7.1 to 12.1
Lower limb weakness	0.56	11.273	.000	0.1 to 0.1
Overall lower limb sensation	−0.15	−2.868	.004	−2.4 to −0.5
Neglect	−0.15	−2.923	.004	−3.5 to −0.7
Mobility				
(Constant)		6.31	.00	1.0 to 1.9
Lower limb weakness	0.4	7.1	.00	0.01 to 0.02
Overall lower limb sensation	−0.1	−1.6	.12	−0.33 to 0.04
Neglect	−0.1	−1.6	.11	−0.46 to 0.05
Balance				
(Constant)		6.5	.0	1.2 to 2.23
Lower limb weakness	0.53	9.8	.0	0.02 to 0.02
Overall lower limb sensation	−0.1	−1.8	.07	−0.39 to 0.01
Neglect	−0.1	−1.8	.01	−0.55 to 0.02

of both sensory modalities. Because this pooled individual analysis includes most of the data on sensory modalities published in recent years, there is little to compare this with, but the frequency of sensory impairments is somewhat lower than other reports.[1,2] This may be explained by differences in the measurement tools used: The selected studies mainly used simple clinical tests, whereas the other reports[1,2] used more sensitive instrumented measures of discrimination. The instrumented measures may provide a more sensitive and detailed analysis of the impairment. However, the extent to which they are relevant to function is unclear; the more subtle impairments they detected may be insufficient to have an impact on activity.

Our results confirm that sensation (proprioception and tactile sensation combined) has a significant independent impact on activity, in that people with sensory impairments were less able. The significance of the combined impairment of both proprioception and tactile sensation suggests that interventions targeting both modalities may have more effect on function than interventions that focus on single modalities. Furthermore, the high internal consistency of these tests demonstrates that they could be considered a single construct. These results challenge the traditional view that sensory modalities are different entities that need to be assessed and treated separately and support the more recent suggestions that the pathways and network for these modalities are integrated and distributed.[30,31] Compared with the motor system, relatively little is known about the neural mechanisms underlying sensory impairments and recovery. Further research is needed to understand these mechanisms and to model and develop effective interventions and measurement tools to aid recovery.

A neural network model with integrated sensory modalities offers the possibility that treatments could be generalized because they would enable recovery between modalities. If this is the case, interventions that target any, or all, aspects of sensation may be effective. Support for this hypothesis is provided by our finding that sensation (proprioception and tactile sensation combined) is an independent factor in balance control or mobility, but each single modality was not. This is contrary to the prevalent view that proprioception is the predominant modality related to balance and mobility disturbance and indicates the need to further explore sensory redundancy and the ways sensory modalities are perceived and filtered according to task and environment. Including standardized sensory assessments and a range of modalities in future trials would test this hypothesis further.

At present, the evidence for therapy interventions to improve sensory impairment is inconclusive.[32,33] Intensive practice of functional tasks is known to be beneficial for motor impairments and activity limitations[34] but may also affect sensation because the tasks challenge the sensory system and require integration of motor and sensory systems, rather than acting on the motor system in isolation. Support for this comes from the observation that sensation improves even in the absence of specific sensory interventions.[35] Future trials of intensive practice of functional tasks and other interventions that focus on motor performance should also include measures of sensation to test this hypothesis.

The only factors of the ones we measured that affected sensory loss were other stroke-related impairments. This is not a surprise because the size and location of the stroke lesion are known to be the biggest factors affecting stroke severity and recovery.[36] However, spasticity did not affect sensory impairments or function. This lends further support to the growing evidence that spasticity is only a problem for a minority of stroke survivors and for most is an epi-phenomenon.[37-40] More surprising was the finding that time since stroke was not a significant factor. This may suggest that sensory impairment does not recover with time; however, prospective longitudinal studies show this is not the case.[22,35] A more likely explanation is the heterogeneity of the time since stroke allowed by the inclusion criteria.

Limitations

To our knowledge, this is the first pooled analysis of individual data of this type, and it has involved all of the available sensory data on the lower limb collected in recent years; it is therefore as complete as we could make it. However, the analysis was pragmatic and we did not use sample size calculations, so some of the conclusions may be underpowered. In fulfilling our aim to be as inclusive and comprehensive as possible, we chose broad inclusion criteria. This is both a strength, in that it enables a representative view, and a weakness, because the ensuing heterogeneity may have made it harder to draw clear conclusions. Finally, we recoded some balance and mobility data into less detailed and generic terms to enable comparison; in doing so, we may have lost some detail.

Conclusions

Poststroke touch and proprioception in the lower limb are often grossly preserved, but where there is impairment, functional activity is affected. These 2 sensory modalities seem to be intimately integrated, and our results suggest that treating these impairments during functional tasks, rather than individually through sensory retraining, may be an effective treatment. Further research to evaluate this approach and to elucidate the mechanisms of recovery is warranted.

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APPENDIX

Recoding of Sensory, Balance, and Mobility Data

Tactile sensation data	Absent	Impaired	Normal/ Intact
Generic score, adopted from Tyson et al[20]	3	2	1
Original RASP[27] scores	0-1	2-5	6
Original EmNSA[23] and NSA[26] scores	0	1	2
Original Siemmes-Weinstein filament log values[24]	3.62	4.31	4.56/6.65

Proprioception data	Absent	Impaired	Present
Generic score, adopted from Tyson et al[20]	3	2	1
Original RASP[28] scores	0-1	2-5	6
Original NSA[27] scores for detection	0	–	1-3
Original NSA[27] scores for discrimination	0-1	2	3
Original EmNSA[23] scores for detection	0	–	1-2
Original EmNSA[23] scores for discrimination	0	1	2
Distal proprioception test[26]	0-2	3-8	9-10

Balance data	Generic score	BBA scores	Berg scores	GF-RMA scores
Very severe balance deficit (sitting balance only)	1	0-3	0-15	1-3
Severe balance deficit (standing balance only)	2	4-6	16-31	4-5
Moderate balance deficit (walking)	3	7-9	32-43	6
Mild balance deficit (advance balance activities)	4	10-12	44-56	7+

Mobility data	Generic score	Iowa scores	RMI scores	GF-RMA scores	FAC scores
Dependent (unable to walk)	1	5-6	0-6	0-5	0
Walks with assistance (requires walking aids or another person)	2	2-4	7	6	1-3
Independently mobile	3	0-1	8+	7+	4-5

Note: BBA = Brunel Balance Assessment; Berg = Berg Balance Scale; EmNSA = Erasmus version of the Nottingham Sensory Assessment; FAC = Functional Ambulation Categories; GF-RMA = Gross Function section of the Rivermead Motor Assessment; Iowa = Iowa Level of Assistance Scale; NSA = Nottingham Sensory Assessment; RASP = Rivermead Assessment of Somatosensory Perception; RMI = Rivermead Mobility Index.