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Beyond Functional Recovery After Stroke: A Longitudinal Mixed-Methods Study of Unresolved Recovery Needs Using Home-Based Wearable Monitoring

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Article

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Abstract

Background

Functional recovery after stroke may not fully reflect how patients experience recovery in everyday life. This study examined multidomain recovery by integrating functional assessment, home-based wearable monitoring, and patient-perceived recovery.

Methods

A prospective longitudinal explanatory sequential mixed-methods study followed 186 adults with stroke for 6 months after discharge. Functional recovery was assessed using the Fugl-Meyer Assessment motor domain and Barthel Index. Nocturnal heart rate variability, sleep efficiency, and daily step count were obtained through repeated 7-day home-based monitoring. Recovery patterns were identified using model-based clustering in 158 participants with complete valid data. Semistructured interviews were then conducted with 28 participants purposively selected across recovery patterns, and qualitative findings were integrated with quantitative trajectories.

Results

Four recovery patterns were identified: concordant multidomain recovery (58/158, 36.7%), functional-predominant discordant recovery (47/158, 29.7%), gradual multidomain recovery (31/158, 19.6%), and limited multidomain recovery (22/158, 13.9%). Participants with functional-predominant discordant recovery showed substantial functional improvement but comparatively limited changes in heart rate variability, sleep efficiency, and daily step count. Interviews revealed persistent fatigue, sleep-related difficulties, uncertainty about physical capacity, and difficulty resuming previous routines and roles despite greater functional independence.

Conclusion

Functional improvement after stroke did not always correspond to physiological-behavioral or patient-perceived recovery. Nearly one third of participants showed functional-predominant recovery discordance. Postdischarge nursing assessment should therefore extend beyond functional independence and consider patients' everyday recovery experiences and, where appropriate, longitudinal wearable-derived information.

1. Introduction

Recovery after stroke is still judged largely by gains in motor function, independence in activities of daily living, and disability status [1, 2]. These outcomes are essential because they capture whether patients

are regaining the ability to move and manage everyday tasks. Yet improvement on functional measures does not necessarily mean that recovery feels complete to the patient. Fatigue and sleep disturbance remain common after stroke and may interfere with recovery and participation [3, 4], while difficulties in social participation or resuming previous roles can persist even after basic independence has improved [5, 6]. Patients who appear to be recovering well on conventional functional assessments may therefore continue to have important needs after discharge.

Recovery also involves physiological and behavioral changes that may not follow the same course as motor improvement. Stroke can affect autonomic regulation, sleep, and physical activity [7, 8], and these changes may persist independently of the degree of functional impairment [7, 9]. Likewise, being able to walk or perform activities of daily living does not necessarily translate into comparable activity levels at home or in the community [10, 11]. Wearable studies have shown that clinically measured motor capacity and real-world activity are related but distinct, particularly as patients move from supervised rehabilitation into everyday living [12, 13]. Functional improvement observed in clinical settings may therefore provide only part of the picture of recovery in daily life.

This distinction becomes more relevant after hospital discharge, when much of recovery takes place outside direct clinical observation. Home-based wearable monitoring can provide repeated information on physiological regulation, sleep, and physical activity under usual living conditions [14, 15, 20]. Such information may help characterize changes that are difficult to capture through intermittent clinic visits alone. Wearable-derived measures, however, should not be treated as diagnostic indicators or substitutes for established functional assessments. Their value is more likely to lie in adding longitudinal context between clinical encounters. This is particularly relevant to nursing care, because nurses contribute to posthyperacute assessment, discharge preparation, patient education, and coordination of stroke care [31].

Objective measures alone also cannot capture how patients understand their own recovery. Stroke survivors often describe recovery in terms of fatigue, bodily stability, confidence in their physical condition, the ability to sustain activity, and whether they can return to familiar routines and social roles [16, 17]. These aspects of recovery may remain limited even when motor function and independence have improved [16–19]. After discharge, such discrepancies may be especially important because unresolved needs can become less visible once basic functional independence has been regained.

A clearer understanding of poststroke recovery therefore requires functional status, physiological-behavioral change, and patient-perceived recovery to be considered together. Previous wearable studies have largely focused on sensor-derived or functional outcomes, whereas qualitative studies have examined how stroke survivors experience recovery in everyday life [15, 16, 20]. These perspectives have rarely been examined longitudinally within the same cohort. It remains uncertain whether substantial functional improvement is accompanied by comparable physiological-behavioral recovery and whether these changes align with how patients themselves experience recovery. This gap matters clinically

because favorable functional outcomes may coexist with continuing needs that are not readily identified through conventional assessment alone.

The present study used a prospective longitudinal explanatory sequential mixed-methods design to examine recovery after stroke across functional, wearable-derived physiological-behavioral, and patient-perceived domains. The aims were to identify multidomain recovery patterns, assess whether functional and physiological-behavioral recovery progressed concordantly within individuals, and explore how patients experienced recovery across the identified patterns. Particular attention was given to patients who showed substantial functional improvement but limited physiological-behavioral recovery and continued to perceive their recovery as incomplete. By integrating conventional functional assessment, home-based wearable monitoring, and patient experience, the study sought to clarify recovery needs that may remain less apparent during routine postdischarge follow-up.

2. Methods

2.1. Study design and participants

This study used a prospective longitudinal explanatory sequential mixed-methods design to examine poststroke recovery across functional, wearable-derived physiological-behavioral, and patient-perceived domains. Participants were recruited from three tertiary hospitals in the Republic of Korea between February and May 2025 and were followed for 6 months. The final 6-month follow-up assessment was completed in November 2025. Participants were recruited before hospital discharge, whereas postdischarge wearable monitoring and follow-up assessments were conducted in home and community settings.

Eligible participants were adults aged 18 years or older with ischemic or hemorrhagic stroke confirmed by neuroimaging who were expected to return home after discharge and were able to participate in the planned follow-up assessments and wearable monitoring. Participants were also required to have sufficient communication ability to describe their recovery experiences and provide informed consent. Exclusion criteria were persistent atrial fibrillation or the presence of a cardiac pacemaker, which could affect the interpretation of wearable-derived heart rate variability; severe cognitive or communication impairment that prevented follow-up assessment or wearable use; and a severe medical condition expected to interfere with longitudinal follow-up.

The study proceeded in two sequential phases followed by mixed-methods integration. In the quantitative phase, functional assessments and home-based wearable measurements were collected repeatedly over the 6-month follow-up period to characterize longitudinal changes and identify patterns of concordance or discordance between functional and physiological-behavioral recovery. The resulting quantitative recovery patterns were then used to guide purposive sampling for the qualitative phase. One-to-one semistructured interviews were conducted to explore how participants experienced recovery in relation to their bodies, daily activities, and return to previous routines and roles. Quantitative recovery

trajectories, wearable-derived measures, and interview findings were subsequently linked at the individual level and integrated to interpret similarities and differences across recovery domains. The overall study sequence and mixed-methods integration process are shown in Fig. 1.

The study size was determined pragmatically by recruiting eligible patients during the predefined recruitment period from February to May 2025. No formal a priori power calculation was performed because the primary quantitative objective was to characterize longitudinal multidomain recovery patterns using repeated measures and data-driven clustering rather than to test a single prespecified treatment effect or between-group hypothesis. The stability and interpretability of the resulting recovery-pattern solution were evaluated using cluster size, posterior classification probability, bootstrap resampling, and sensitivity analyses.

2.2. Longitudinal data collection and measures

Quantitative data were collected at a pre-discharge assessment and during repeated postdischarge follow-up. The assessment schedule and measures obtained at each time point are summarized in Table 1.

Functional assessments were conducted within 72 hours before the anticipated discharge date and were repeated at 1, 3, and 6 months after discharge. Functional recovery was assessed using the Fugl-Meyer Assessment motor domain (FMA-Motor) and the Barthel Index (BI), which were analyzed as separate measures rather than combined into a composite score [2, 21–23].

Wearable monitoring followed a slightly different baseline schedule because free-living physiological and behavioral measurements could only be obtained after participants returned to their usual environment. The initial 7-day wearable monitoring period began within 48 hours after discharge, with additional 7-day monitoring periods at the 1-, 3-, and 6-month follow-up points. Thus, the pre-discharge assessment served as the baseline for functional measures, whereas the first postdischarge 7-day monitoring period served as the baseline for wearable-derived measures. Functional assessments and wearable monitoring were scheduled as closely as possible within each subsequent follow-up window.

Physiological data were collected in participants' homes using the Bittium Faros 180L (Bittium Biosignals Ltd., Oulu, Finland), which recorded continuous single-lead electrocardiography (ECG). All devices were configured at a sampling frequency of 250 Hz, and raw ECG recordings were stored in European Data Format. Standardized recording settings were applied before each monitoring period using Bittium Faros Manager. After each monitoring period, raw ECG files were transferred via Micro-USB to an access-restricted, encrypted research computer. R-R intervals derived from normal beats were used to calculate the root mean square of successive differences (RMSSD) and the standard deviation of normal-to-normal intervals (SDNN).

Behavioral data were collected using the same Galaxy Watch7 model (Samsung Electronics Co., Ltd., Suwon, Republic of Korea) provided to all participants for study use. Participants wore the device on the

same wrist during each monitoring period. The smartwatch was paired with a study Android smartphone and synchronized with Samsung Health. A study-specific Android application retrieved participant-authorized sleep and activity data through the Samsung Health software development kit available during the study and linked each record to the participant study identification number and time stamp. Device, operating system, Samsung Health, and data-extraction software versions were recorded during the study to support reproducibility of the digital data-collection process.

Wearable-derived sleep and activity measures were used as longitudinal indicators of behavioral recovery rather than as diagnostic measures. Total sleep time, sleep efficiency, daily step count, and activity time were retained for analysis, whereas manufacturer-generated sleep scores and composite health scores were not used. Sleep efficiency was calculated as total sleep time divided by the duration of the main sleep period, defined from bedtime to final wake time, multiplied by 100. Because the smartwatch was a consumer-grade device, sleep-derived measures were interpreted as indicators of within-person change over time rather than as substitutes for clinical sleep assessment [24].

Participants were instructed to maintain their usual sleep and physical activity patterns during each 7-day monitoring period. ECG, sleep, and activity data were aligned using participant study identification numbers and time stamps and were matched to the functional assessment obtained within the corresponding follow-up window. Device models remained unchanged throughout the study.

Table 1
Schedule of longitudinal data collection and measures

Measure/domain	**Pre-discharge ≤ 72 h**	**Early post-discharge ≤ 48 h start**	**1 month**	**3 months**	**6 months**	**Data source**
Demographic and clinical data	J					Medical record
FMA-Motor	J		J	J	J	Clinical assessment
Barthel Index	J		J	J	J	Clinical assessment
ECG / RMSSD, SDNN		7 days	7 days	7 days	7 days	Bittium Faros 180L
Sleep efficiency / total sleep time		7 days	7 days	7 days	7 days	Galaxy Watch7
Daily steps / activity time		7 days	7 days	7 days	7 days	Galaxy Watch7
Qualitative interview					After pattern classification	Semi-structured interview

2.3. Wearable data processing and feature extraction

Wearable data were processed using the same prespecified procedures across all assessment points. Raw ECG signals sampled at 250 Hz were processed using a standardized preprocessing pipeline. Technical artifacts and nonnormal beats were identified and excluded before heart rate variability analysis, and RMSSD and SDNN were calculated from the resulting normal-to-normal R-R intervals [25, 26].

To reduce variation associated with daytime physical activity and behavioral state, the primary heart rate variability analysis was restricted to nocturnal ECG segments that overlapped with the main sleep period identified from the Galaxy Watch data. A night was considered valid when at least 4 hours of analyzable ECG data were available and at least 80% of detected R-R intervals remained valid after artifact and abnormal-beat screening.

Total sleep time, sleep efficiency, daily step count, and activity time were derived from the Galaxy Watch data. Validity was determined separately for each primary wearable-derived measure within each 7-day monitoring window. RMSSD was considered valid when at least 4 nights met the prespecified ECG validity criteria. Sleep efficiency was considered valid when usable sleep data were available for at least 4 nights, and daily step count was considered valid when usable activity data were available for at least 4 days. Total sleep time and activity time followed the corresponding sleep and activity validity criteria.

If the validity criterion for one wearable-derived measure was not met at a given assessment point, only that measure at that assessment point was treated as missing. Other wearable-derived measures were retained when their respective validity criteria were satisfied.

ECG, sleep, and activity data were aligned by date and time and matched to the functional assessment from the corresponding follow-up window. RMSSD was designated as the primary physiological measure, whereas sleep efficiency and daily step count were designated as the primary behavioral measures. SDNN, total sleep time, and activity time were retained as supplementary measures and were used in sensitivity analyses. Additional preprocessing procedures are provided in the **Supplementary Methods**.

2.4. Operational definition of recovery discordance and derivation of recovery patterns

Recovery discordance was operationalized as divergence between functional recovery and wearable-derived physiological-behavioral recovery within the same individual. It was used as an analytical construct to characterize between-domain differences in longitudinal recovery and was not intended as a diagnostic criterion, clinical classification, or validated phenotype. Patient-perceived recovery was not used to derive the quantitative recovery patterns and was examined subsequently during qualitative analysis and mixed-methods integration.

For functional measures, baseline was defined as the pre-discharge assessment conducted within 72 hours before discharge. For wearable-derived measures, baseline was defined as the initial 7-day home-monitoring period beginning within 48 hours after discharge. These different baseline points reflected the timing at which each type of measure could be meaningfully obtained in its intended setting.

The primary recovery-pattern analysis included five longitudinal measures: FMA-Motor and the Barthel Index for functional recovery, RMSSD for physiological recovery, and sleep efficiency and daily step count for behavioral recovery. SDNN, total sleep time, and activity time were not included in the primary clustering model to avoid disproportionate weighting of closely related measures within the same domain and were retained for sensitivity analyses.

For each of the 5 primary measures, participant-specific longitudinal trajectories were estimated from repeated measurements using linear mixed-effects models with time in months entered as a continuous variable and participant-specific random intercepts and random slopes. The participant-specific slope was used to summarize the overall rate of change across the 6-month follow-up period, and the corresponding model-estimated change over 6 months was derived from this trajectory. Each resulting change estimate was divided by the baseline SD of the corresponding measure to place variables expressed in different units on a comparable scale. Score directions were aligned so that 0 represented no estimated longitudinal change and positive values consistently represented change toward better recovery. These standardized change estimates were not mean-centered around the sample mean.

Recovery patterns were derived from the joint distribution of the five standardized longitudinal change estimates using model-based clustering rather than prespecified clinical cutoffs. Cluster labels were assigned only after the statistical solution had been selected and were based on the relative configuration of functional, physiological, and behavioral changes within each cluster. Patterns in which functional and physiological-behavioral measures improved together were interpreted as concordant multidomain recovery, whereas patterns characterized by substantial functional improvement accompanied by comparatively limited physiological or behavioral change were interpreted as functional-predominant recovery discordance.

After the quantitative recovery patterns had been established, participants were purposively selected for the qualitative phase. Interview findings were then linked at the individual level with participants' functional and wearable-derived recovery trajectories. Patient-perceived recovery therefore served as an interpretive dimension during mixed-methods integration rather than as an input to the quantitative clustering procedure.

2.5. Qualitative data collection

Participants for the qualitative phase were purposively sampled from those who completed the 6-month follow-up and were selected on the basis of the quantitatively derived recovery patterns. Sampling was designed to include participants from the major recovery patterns while also considering variation in age,

sex, and stroke type. Eligible participants were approached individually after the quantitative recovery patterns had been identified.

Sampling continued until the interviews provided sufficient depth and variation in recovery experiences across the identified patterns to address the qualitative study question. The purpose of sampling was not to estimate the prevalence of specific experiences, but to obtain detailed accounts that could help explain how quantitatively observed recovery patterns were experienced in everyday life.

One-to-one semistructured interviews were conducted by the author, a female PhD-prepared registered nurse and university faculty member with formal training in qualitative research. The researcher had no prior relationship with the participants before study enrollment, and participants were not informed of their quantitative recovery pattern before the interview.

Open-ended questions included, “How do you feel your recovery has progressed since discharge?” and “Which aspects of your daily life feel recovered, and which do not yet feel recovered?” Follow-up questions explored physical function, sleep and activity, confidence in the body, symptoms or discomfort, and changes in everyday and social roles. When discrepancies were identified between functional assessment results and participants’ experiences of recovery, the interviewer explored how these differences appeared in daily life without directing participants toward a particular response. Patient-perceived recovery was understood as participants’ own appraisal of bodily recovery, confidence in sustaining everyday activities, and ability to resume personally meaningful routines and roles.

Interviews were conducted in a private setting and lasted approximately 40–60 minutes. No nonparticipants were present, and no repeat interviews were conducted. With participants’ consent, all interviews were digitally recorded and transcribed verbatim by the researcher. Identifying information was removed from the transcripts. Immediately after each interview, key observations, contextual information, and issues for further consideration were documented in research notes.

2.6. Data analysis

2.6.1. Quantitative analysis

Participant characteristics were summarized using frequencies and percentages, means and SDs, or medians and interquartile ranges, as appropriate. Baseline characteristics of participants included in and excluded from the recovery-pattern analysis were compared using independent-samples t tests, Mann-Whitney U tests, chi-square tests, or Fisher exact tests according to variable type and distribution.

Group-level longitudinal changes in functional, physiological, and behavioral measures were examined using linear mixed-effects models. Assessment time was entered as a categorical fixed effect, participant as a random intercept, and study site as a fixed effect. RMSSD and daily step count were log-transformed before modeling because of their skewed distributions. All available repeated observations were included using maximum likelihood estimation.

Recovery-pattern derivation was based on repeated measurements of FMA-Motor, the Barthel Index, RMSSD, sleep efficiency, and daily step count. For each measure, participant-specific longitudinal trajectories were estimated using a linear mixed-effects model with time in months entered as a continuous variable and participant-specific random intercepts and random slopes. The participant-specific slope represented the individual rate of change across the follow-up period and was used to derive the corresponding model-estimated change over 6 months. Time was modeled continuously for recovery-pattern derivation because the aim was to obtain a parsimonious participant-level summary of the overall direction and magnitude of change across follow-up rather than to model the detailed shape of the population-level recovery trajectory. Each model-estimated change was divided by the baseline SD of the corresponding measure to place variables expressed in different units on a comparable scale. Score directions were aligned so that positive values consistently represented change toward better recovery.

Model-based clustering was performed using the five standardized longitudinal change measures within a Gaussian finite-mixture framework. Solutions containing two to six clusters were compared. The Bayesian information criterion (BIC) was used as the primary criterion for selecting the number of clusters, together with cluster size and posterior classification probability. Cluster stability was assessed using 500 bootstrap resamples, and agreement between the original and bootstrap-derived classifications was quantified using the adjusted Rand index. Sensitivity analyses were conducted by substituting SDNN, total sleep time, and activity time for the corresponding primary variables to examine the robustness of the identified recovery patterns.

Missing repeated observations in the overall longitudinal analyses were handled through maximum likelihood estimation. The recovery-pattern analysis was restricted to participants who completed the 6-month follow-up and had valid data for all five primary recovery measures at each required assessment point. A complete set of primary measures was required for clustering so that each participant's multidomain recovery profile was derived from the same measurement domains across comparable follow-up periods. Participants with missing or invalid data for any primary recovery measure at one or more required assessment points were therefore excluded from the recovery-pattern analysis.

All statistical tests were two-sided, with a significance level of .05. Analyses were conducted using R version 4.6.1 (R Foundation for Statistical Computing).

2.6.2. Qualitative analysis

Interview data were analyzed using reflexive thematic analysis [27]. Transcripts were read repeatedly to develop familiarity with each participant's account of recovery. Initial codes were generated directly from the interview data and were subsequently examined in relation to experiences of functional change, bodily and physiological changes, everyday life, and patient-perceived recovery. Related codes were developed into provisional themes, which were refined through repeated comparison with the original transcripts.

To preserve the explanatory sequential structure of the study, the quantitatively derived recovery patterns were not used to guide the initial coding process. After the qualitative themes had been developed, similarities and differences in experiences were compared across participants from the different quantitative recovery patterns. The author conducted the qualitative analysis and maintained research notes and analytic memos throughout the analytic process to document coding decisions, theme development, and alternative interpretations. To support analytic reflexivity, the developing themes and their interpretation were discussed through peer debriefing with an experienced qualitative nursing researcher who was not involved in participant recruitment, data collection, or the quantitative analysis. The discussion focused on the coherence of the developing themes and consideration of alternative interpretations. The external researcher did not independently code the transcripts or determine the final themes, and final analytic decisions remained with the author. Cases that did not fit the emerging interpretation were revisited before the final themes were defined.

Qualitative data were coded manually without dedicated qualitative analysis software. Transcripts were not returned to participants for comment or correction, and participant checking of the final themes was not conducted.

2.6.3. Mixed-methods integration

Quantitative and qualitative findings were integrated through connecting and merging. First, the recovery patterns identified in the quantitative analysis were used to guide purposive selection of participants for the qualitative interviews. Second, each participant's functional recovery trajectory, wearable-derived physiological-behavioral changes, and interview-based recovery experience were linked at the individual level.

Integrated findings were summarized by recovery pattern using a joint display to examine how quantitative recovery trajectories corresponded with participants' experiences of recovery. In Fig. 4, the functional recovery estimate was calculated as the mean of the standardized change scores for FMA-Motor and the Barthel Index, whereas the physiological-behavioral recovery estimate was calculated as the mean of the standardized change scores for RMSSD, sleep efficiency, and daily step count.

Pattern-specific 95% CIs for these domain-level means were estimated using 1,000 nonparametric bootstrap resamples, with participants as the resampling unit within each pattern. The between-domain difference (Δ) was calculated as functional recovery minus physiological-behavioral recovery. These domain-level summaries were used only to visualize and interpret the integrated findings and were not used to derive the recovery-pattern clusters.

2.7. Ethical considerations

The study was approved by the Institutional Review Board of the Korea Institute for Health Affairs (IRB No. BS25Ga14586) before participant recruitment. All participants received written and verbal information about the study purpose and procedures, wearable-based data collection, potential

discomforts, privacy protection, and their right to withdraw from the study without disadvantage. Written informed consent was obtained from all participants before enrollment.

Participants selected for the qualitative phase provided additional consent for audio recording and transcription of the interviews. Clinical, wearable, and interview data were managed using study identification numbers after removal of directly identifying information. The same study identification numbers were used to link quantitative and qualitative data during mixed-methods integration. Research data were stored in access-restricted, encrypted storage and were accessible only for research purposes. The study was conducted in accordance with the principles of the Declaration of Helsinki.

Clinical trial number: not applicable.

3. Results

3.1. Participant characteristics

A total of 186 participants with stroke were enrolled, of whom 164 (88.2%) completed the 6-month follow-up. Follow-up ended before 6 months for 22 participants. Among the 164 participants who completed follow-up, 6 had missing or invalid data for one or more of the five primary recovery measures and were therefore excluded from the recovery-pattern analysis. Accordingly, 158 participants were included in the recovery-pattern analysis. Variable-specific data completeness is summarized in **Supplementary Table S1**.

The mean age of the total cohort was 64.1 years (SD 11.3), 108 participants (58.1%) were men, and 143 (76.9%) had ischemic stroke. At the pre-discharge assessment, the mean FMA-Motor score was 62.8 (SD 18.7), and the mean Barthel Index score was 68.4 (SD 17.6). No statistically significant differences in major baseline characteristics were observed between participants included in and excluded from the recovery-pattern analysis (Table 2).

Table 2
Baseline characteristics of study participants

Characteristics	Total cohort (N = 186)	Recovery-pattern analysis (n = 158)	Excluded (n = 28)	P value
Sociodemographic characteristics				
Age, years	64.1 (11.3)	63.8 (11.1)	65.8 (12.2)	.39
Male sex	108 (58.1)	92 (58.2)	16 (57.1)	.91
Living alone	39 (21.0)	32 (20.3)	7 (25.0)	.57
Employed before stroke	66 (35.5)	58 (36.7)	8 (28.6)	.41
Stroke characteristics				
Ischemic stroke	143 (76.9)	123 (77.8)	20 (71.4)	.46
Hemorrhagic stroke	43 (23.1)	35 (22.2)	8 (28.6)	
Right-sided lesion	92 (49.5)	78 (49.4)	14 (50.0)	.95
Left-sided lesion	94 (50.5)	80 (50.6)	14 (50.0)	
First-ever stroke	159 (85.5)	136 (86.1)	23 (82.1)	.58
Time from stroke onset to discharge, days	18 (12–29)	18 (12–28)	20 (13–31)	.47
NIHSS score at baseline	5 (3–8)	5 (3–8)	6 (3–9)	.31
Modified Rankin Scale score at baseline	3 (2–3)	3 (2–3)	3 (2–4)	.44
Clinical characteristics				
Hypertension	124 (66.7)	105 (66.5)	19 (67.9)	.89
Diabetes mellitus	58 (31.2)	49 (31.0)	9 (32.1)	.91
Cardiovascular disease	25 (13.4)	20 (12.7)	5 (17.9)	.45
β-blocker use	29 (15.6)	24 (15.2)	5 (17.9)	.72
Baseline functional status				
FMA-Motor score	62.8 (18.7)	63.4 (18.2)	59.4 (21.1)	.29
Barthel Index score	68.4 (17.6)	69.1 (17.2)	64.5 (19.5)	.20

Note. Data are presented as mean (SD), median (IQR), or n (%), as appropriate. *p* values compare participants included in the recovery-pattern analysis with those excluded. Continuous variables were compared using the independent-samples t test or Mann–Whitney U test as appropriate, and categorical variables using the χ^2 test or Fisher's exact test. FMA-Motor, Fugl–Meyer Assessment motor domain; NIHSS, National Institutes of Health Stroke Scale.

3.2. Longitudinal Changes in Functional and Wearable-derived Recovery Measures

The linear mixed-effects models included all available repeated observations from the 186 enrolled participants. Functional measures showed the greatest improvement during the first 3 months after discharge. The observed mean FMA-Motor score increased from 62.8 (SD 18.7) before discharge to 72.0 (SD 17.2) at 1 month, 78.5 (SD 15.8) at 3 months, and 81.2 (SD 15.1) at 6 months. The overall effect of time was statistically significant (P<.001), and the model-estimated mean difference between the pre-discharge and 6-month assessments was 18.3 points (95% CI 16.4–20.2).

The mean Barthel Index score increased from 68.4 (SD 17.6) before discharge to 79.8 (SD 15.4) at 1 month, 86.6 (SD 12.8) at 3 months, and 88.9 (SD 11.9) at 6 months. The overall effect of time was statistically significant (P<.001), with a model-estimated mean difference of 20.5 points (95% CI 18.6–22.4) between the pre-discharge and 6-month assessments. For both functional measures, improvement was smaller between 3 and 6 months than during the earlier follow-up period.

Nocturnal RMSSD increased from a median of 24.7 ms (IQR 18.5–32.6) during the initial postdischarge monitoring period to 25.6 ms (IQR 19.1–33.8) at 1 month, 27.3 ms (IQR 20.3–35.5) at 3 months, and 27.9 ms (IQR 20.5–36.3) at 6 months. In the linear mixed-effects model fitted after log transformation, the overall effect of time was statistically significant (P=.021).

Wearable-derived behavioral measures also changed over time. Mean sleep efficiency increased from 78.9% (SD 8.0) during the initial postdischarge monitoring period to 80.2% at 1 month, 82.0% at 3 months, and 82.3% at 6 months (P=.010). Median daily step count increased from 3,260 steps (IQR 2,110–4,670) during the initial monitoring period to 4,380 (IQR 2,960–5,950) at 1 month, 5,190 (IQR 3,520–6,900) at 3 months, and 5,360 (IQR 3,650–7,060) at 6 months (P<.001). Changes in both sleep efficiency and daily step count were smaller between 3 and 6 months than during the earlier follow-up period.

At the group level, functional, physiological, and behavioral measures changed in the direction of recovery, although the magnitude and timing of change differed across domains. Functional measures showed more rapid improvement during the first 3 months, whereas changes in nocturnal RMSSD and sleep efficiency were more gradual (Fig. 2).

Note

Points represent observed summary values at each assessment point (means for FMA-Motor, Barthel Index, and sleep efficiency; medians for RMSSD and daily steps). p values indicate the overall effect of time from linear mixed-effects models adjusted for study site. The number of available observations varied across follow-up points. RMSSD and daily steps were log-transformed for model-based inference. FMA-Motor, Fugl–Meyer Assessment motor domain; RMSSD, root mean square of successive differences.

3.3. Recovery patterns and recovery discordance

The recovery-pattern analysis included 158 participants who completed the 6-month follow-up and had valid data for all five primary recovery measures at each required assessment point. Gaussian finite-mixture models containing two to six clusters were compared. The four-cluster solution provided the best fit according to the prespecified model-selection criteria, with a ΔBIC of 6.4 relative to the next-best solution. The mean maximum posterior classification probability was 0.87, and the mean adjusted Rand index across 500 bootstrap resamples was 0.80.

In sensitivity analyses in which SDNN, total sleep time, and activity time were substituted for the corresponding primary measures, the four-cluster structure was retained. Agreement with the primary classification was 84.2%, with an adjusted Rand index of 0.73. The four-cluster solution was therefore retained for subsequent analyses (Table 3 **and** Fig. 3).

Pattern 1, concordant multidomain recovery, included 58 of 158 participants (36.7%). Mean standardized model-estimated changes were + 1.10 for FMA-Motor, + 1.05 for the Barthel Index, + 0.72 for RMSSD, + 0.68 for sleep efficiency, and + 0.92 for daily step count. This pattern was characterized by improvement across functional, physiological, and behavioral domains.

Pattern 2, functional-predominant discordant recovery, included 47 participants (29.7%). Mean standardized changes were + 1.02 for FMA-Motor and + 0.96 for the Barthel Index, compared with + 0.05 for RMSSD, + 0.09 for sleep efficiency, and + 0.18 for daily step count. Thus, substantial functional improvement was accompanied by comparatively limited physiological-behavioral change.

Pattern 3, gradual multidomain recovery, included 31 participants (19.6%). Mean standardized changes were + 0.45 for FMA-Motor, + 0.41 for the Barthel Index, + 0.36 for RMSSD, + 0.31 for sleep efficiency, and + 0.38 for daily step count. Improvement was observed across all three recovery domains, but the magnitude of change was smaller than in Pattern 1.

Pattern 4, limited multidomain recovery, included 22 participants (13.9%). Mean standardized changes were + 0.12 for FMA-Motor, + 0.08 for the Barthel Index, − 0.11 for RMSSD, − 0.07 for sleep efficiency, and + 0.03 for daily step count. Changes were limited across functional, physiological, and behavioral measures.

Overall, 47 of 158 participants (29.7%) showed functional-predominant recovery discordance. The standardized model-estimated changes across the five primary recovery measures and their distribution across the four patterns are presented in Fig. 3.

Table 3
Characteristics of recovery patterns identified from longitudinal changes

Recovery pattern	n (%)	FMA-Motor	Barthel Index	RMSSD	Sleep efficiency	Daily steps
Pattern 1. Concordant multidomain recovery	58 (36.7)	+ 1.10	+ 1.05	+ 0.72	+ 0.68	+ 0.92
Pattern 2. Functional-predominant discordant recovery	47 (29.7)	+ 1.02	+ 0.96	+ 0.05	+ 0.09	+ 0.18
Pattern 3. Gradual multidomain recovery	31 (19.6)	+ 0.45	+ 0.41	+ 0.36	+ 0.31	+ 0.38
Pattern 4. Limited multidomain recovery	22 (13.9)	+ 0.12	+ 0.08	−0.11	−0.07	+ 0.03

Note. Values are mean standardized model-estimated changes from each measure's corresponding baseline to the 6-month follow-up. For functional measures, baseline was the pre-discharge assessment; for wearable-derived measures, baseline was the initial 7-day monitoring period beginning within 48 hours after discharge. Each participant-level change estimate was divided by the baseline SD of the corresponding measure and was not mean-centered. Thus, 0 indicates no estimated change, and positive values indicate change in the direction of better recovery.

Note

Panel A shows mean standardized model-estimated changes from each measure's corresponding baseline to the 6-month follow-up within the 4 recovery patterns; 0 indicates no change and positive values indicate change in the direction of better recovery. Standardized functional recovery in Panel B is the mean of FMA-Motor and Barthel Index change scores, whereas standardized physiological–behavioral recovery is the mean of RMSSD, sleep efficiency, and daily step change scores. The dashed line represents concordance between the two domain-level summaries (y = x). Δ was calculated as standardized functional recovery minus standardized physiological–behavioral recovery and is descriptive; cluster classification was based on the full five-variable profile rather than on a prespecified Δ threshold. Bubble size is proportional to the number of participants in each pattern. FMA-Motor = Fugl–Meyer Assessment motor domain; RMSSD = root mean square of successive differences.

3.4. Patient-perceived recovery across quantitative recovery patterns

A total of 28 participants completed qualitative interviews: 8 from Pattern 1, 8 from Pattern 2, 6 from Pattern 3, and 6 from Pattern 4. Three themes were identified: (1) the gap between functional improvement and a sense of bodily recovery, (2) bodily stability and confidence in everyday life, and (3) returning to previous routines and roles.

Gap between functional improvement and a sense of bodily recovery

Participants in Pattern 1 generally described improvement in everyday function together with improvements in fatigue, sleep, and overall physical condition. As their activity range expanded, they increasingly described a sense that their bodies were recovering.

"*At first, even a little movement made me stop and rest. Now I can do housework and even go for a walk without much trouble. It is not just that I can walk. My body itself feels more comfortable than before*." (P1-04)

In contrast, participants in Pattern 2 frequently distinguished between being able to perform activities and feeling physically recovered. Although walking and self-care had improved, fatigue, sleep-related difficulties, and prolonged recovery after activity continued to affect daily life.

"*At the hospital, they say I have improved a lot. I can walk around by myself, wash myself, and eat on my own. But I do not feel fully recovered yet. If I do a little too much in one day, my body still feels heavy the next day and I do not want to do anything*." (P2-03)

Participants in Pattern 3 described improvement in both function and physical condition, although these changes were experienced as gradual. Participants in Pattern 4 described persistent functional limitations and physical discomfort that made recovery less apparent in everyday life.

Bodily stability and confidence in everyday life

Perceived recovery was also related to whether participants could anticipate how their bodies would respond to activity. Participants in Pattern 1 reported increasing confidence in regulating activity and rest and became more comfortable going out or performing activities independently.

In Pattern 2, uncertainty about physical capacity persisted despite greater functional independence. Variations in fatigue, sleep, and overall physical condition led some participants to remain cautious about outings and social activities.

"*I can do things, but I still cannot do them without worrying. Just because I feel okay today does not mean I will feel the same tomorrow, so I think a lot before going somewhere far away*." (P2-05)

Participants in Pattern 3 gradually developed confidence by learning their physical limits through everyday experience. In Pattern 4, persistent functional limitations and fluctuations in physical condition continued to restrict confidence in independent activity.

Returning to previous routines and roles

Participants described recovery not only in terms of what they were physically able to do, but also in terms of whether they could resume previous routines and social roles. Participants in Pattern 1 described gradual return to housework, outings, and family activities as important indications of recovery.

In Pattern 2, independence in basic activities did not necessarily translate into confidence in returning to work or other roles requiring sustained activity.

"*At home, I can do almost everything by myself, so other people think I am fully recovered. But if I had to go back to work and keep going from morning until evening, I am still not confident. I do not know whether I could make it through the whole day*." (P2-01)

Participants in Pattern 3 described returning to previous activities in stages. In Pattern 4, continued dependence on others for some activities influenced how participants viewed their own recovery.

"*Being able to walk is important, but my family is still doing some of the things I used to do. When I see that, I feel that I have not really returned to my old life yet*." (P4-05)

Across the four patterns, patient-perceived recovery broadly corresponded with multidomain improvement in Pattern 1. Pattern 2 was characterized by a persistent gap between greater functional independence and a sense of bodily recovery. Pattern 3 reflected gradual improvement across several aspects of recovery, whereas Pattern 4 reflected continuing limitations in both function and everyday experience.

3.5. Mixed-methods integration of recovery patterns and patient-perceived recovery

Individual-level integration of the quantitative and qualitative findings showed different relationships between functional recovery, physiological-behavioral recovery, and patient-perceived recovery across the four recovery patterns (Fig. 4).

In Pattern 1, the standardized functional recovery estimate was 1.08 (95% CI 0.94–1.18), and the physiological-behavioral recovery estimate was 0.77 (95% CI 0.64–0.90). Interview accounts were broadly consistent with these trajectories, with participants describing greater bodily stability, increasing confidence in everyday activities, and progressive resumption of previous routines and roles.

Pattern 2 showed the largest between-domain difference. The standardized functional recovery estimate was 0.99 (95% CI 0.86–1.12), compared with 0.11 (95% CI 0.01–0.20) for physiological-behavioral recovery, yielding a between-domain difference of $\Delta = 0.88$. Participants in this pattern described persistent fatigue, sleep-related difficulties, uncertainty about physical capacity, prolonged recovery after activity, and difficulty resuming work and social roles despite substantial functional improvement.

In Pattern 3, the functional recovery estimate was 0.43 (95% CI 0.31–0.55), and the physiological-behavioral recovery estimate was 0.35 (95% CI 0.24–0.46), yielding a small between-domain difference ($\Delta = 0.08$). Interview accounts similarly reflected gradual improvement in both physical function and everyday bodily experience.

In Pattern 4, both functional recovery [0.10 (95% CI − 0.02 to 0.22)] and physiological-behavioral recovery [− 0.05 (95% CI − 0.15 to 0.05)] were limited, with a between-domain difference of Δ = 0.15. Participants described persistent functional limitations, low confidence in their physical condition, and continued dependence in some everyday activities.

The integrated findings therefore distinguished functional-predominant recovery discordance in Pattern 2 from limited multidomain recovery in Pattern 4. Pattern 2 combined substantial functional improvement with comparatively limited physiological-behavioral change and persistent perceptions of incomplete recovery, whereas Pattern 4 showed limited recovery across functional, physiological-behavioral, and patient-perceived domains.

Note

Functional recovery represents the mean standardized model-estimated change from the pre-discharge assessment to 6 months in FMA-Motor and the Barthel Index, whereas physiological-behavioral recovery represents the mean standardized model-estimated change from the initial postdischarge monitoring period to 6 months in RMSSD, sleep efficiency, and daily step count. Points indicate pattern-level mean standardized change estimates, and horizontal whiskers indicate 95% confidence intervals estimated using within-pattern nonparametric bootstrap resampling. Δ was calculated as functional recovery minus physiological-behavioral recovery; larger positive values indicate greater between-domain divergence. Δ values were calculated from unrounded domain-level estimates. These domain-level summaries were used only to visualize and interpret the integrated findings and were not used to derive the recovery-pattern clusters. Patient-perceived recovery summarizes pattern-specific experiences identified through qualitative interviews. FMA-Motor, Fugl-Meyer Assessment motor domain; RMSSD, root mean square of successive differences.

4. Discussion

4.1. Principal Findings

The most notable finding was that recovery after stroke did not move in parallel across all domains. Functional outcomes improved substantially at the group level, but almost one third of participants showed a different pattern: motor function and independence improved markedly, whereas nocturnal RMSSD, sleep efficiency, and daily step count changed little. The interviews pointed in the same direction. Many participants in this group could manage basic activities independently, yet still did not feel that they had fully recovered in everyday life.

This pattern was different from limited multidomain recovery. In Pattern 4, little improvement was seen across functional, physiological, and behavioral measures, so continuing difficulties were relatively apparent. Pattern 2 was less obvious. These participants had regained considerable functional independence but still described fatigue, sleep-related problems, uncertainty about what their bodies

could tolerate, and difficulty resuming previous routines and roles. A favorable functional score, therefore, did not always mean that recovery-related problems had resolved.

Variation in poststroke recovery is well recognized, particularly in the timing and extent of motor improvement [28]. The present data suggest that variation also occurs across domains within the same person. Functional gains can occur without comparable improvement in physiological regulation, sleep, daily activity, or the patient's own experience of recovery. In this study, recovery discordance was used to describe this within-person difference; it should not be interpreted as a clinical phenotype or diagnostic category.

4.2. Interpretation in relation to previous research

The difference between capacity and everyday performance was particularly visible in Pattern 2. The FMA-Motor and Barthel Index assess what a patient can do under defined conditions, whereas daily activity reflects how that ability is actually used outside the clinic. Previous wearable studies have reported a similar distinction between clinically measured motor capacity and real-world activity [12–14]. Here, motor function and independence improved substantially, but daily step count increased much less. Regaining the ability to perform an activity may therefore precede, or may not fully translate into, sustained activity at home and in the community.

RMSSD provided another view of recovery, although its interpretation requires caution. Autonomic dysfunction may persist after stroke [7, 9], but heart rate variability is affected by age, cardiovascular status, medication, respiration, behavioral state, and recording conditions [26]. The small change in RMSSD observed in the discordant pattern should therefore not be interpreted as direct evidence of incomplete neurological recovery. Its contribution was more useful when considered together with sleep efficiency, activity, and functional change. The fact that several physiological and behavioral measures changed only modestly made the pattern more informative than any single wearable-derived measure would have been.

The interviews helped explain what this numerical discordance meant in daily life. Participants did not describe recovery only in terms of whether they could walk or care for themselves. They also talked about fatigue, the predictability of their physical condition, confidence in sustaining activity, and whether they could return to work or previous social roles. These concerns are consistent with previous evidence on fatigue, participation, and poststroke role resumption [3, 16, 17, 29]. For some participants, being independent in basic activities was therefore not the same as being ready to manage an entire day of work or normal social activity.

4.3. Implications for nursing and postdischarge care

For nurses involved in postdischarge care, the practical concern is that some patients may look functionally recovered while still experiencing substantial difficulty in daily life. Motor scores and independence in activities of daily living remain important, but they may not identify persistent fatigue, poor sleep, limited activity tolerance, or uncertainty about resuming previous roles.

Follow-up assessment may therefore benefit from asking not only what patients can do, but also how consistently they can sustain those activities and how confident they feel doing so. Questions about fatigue, sleep, activity tolerance, participation, and return to previous routines may reveal problems that are not evident from functional measures alone. This is particularly relevant in rehabilitation, discharge planning, transitional care, and community follow-up.

Wearable monitoring may be useful in this context when it provides information that cannot easily be captured during an occasional clinic visit. Its role in this study was not to diagnose recovery problems or replace nursing assessment. Rather, repeated physiological and behavioral measures provided additional context when functional improvement and everyday experience did not appear to match. Given the heterogeneity of wearable devices, algorithms, outcome definitions, and validation methods [20], these measures should still be interpreted cautiously.

The value of combining quantitative and qualitative data was most apparent in Pattern 2. The quantitative analysis showed that functional improvement exceeded physiological-behavioral change, but it did not explain what that difference meant to patients. The interviews showed that the same participants continued to experience fatigue, uncertainty, and difficulty returning to previous roles. Linking these two sources made the discordance clinically interpretable in a way that either source alone could not.

4.4. Strengths and limitations

This study followed the same cohort across repeated functional assessments, home-based wearable monitoring, and qualitative interviews, allowing recovery to be examined from several perspectives within the same individuals. The sequential design also meant that quantitative patterns were established before participants were selected for interviews, after which the findings were integrated at the individual level.

There are several limitations. The recovery-pattern analysis required complete valid data for all five primary measures and included participants who were discharged home and able to complete repeated monitoring; the findings may therefore not represent patients with more severe disability or greater care needs. HRV and consumer-grade sleep and activity measures are also influenced by physiological, behavioral, and device-related factors and were interpreted as indicators of longitudinal change rather than diagnostic measures [24, 30]. In addition, patient-perceived recovery was explored qualitatively rather than measured repeatedly with a validated patient-reported outcome measure. The four recovery patterns were data driven, and their reproducibility should be tested in independent and more diverse stroke populations before they are used for clinical classification.

5. Conclusion

Functional improvement after stroke did not always correspond to recovery across physiological-behavioral or patient-perceived domains. Nearly one third of participants showed substantial functional

gains despite comparatively limited physiological-behavioral change, and their interview accounts described continuing difficulties with fatigue, bodily stability, activity tolerance, and return to previous roles. Postdischarge recovery assessment may therefore benefit from extending beyond functional independence alone. Combining conventional functional assessment with attention to everyday recovery experiences and, where appropriate, longitudinal wearable-derived information may provide a more complete understanding of continuing recovery needs after stroke.

Abbreviations

FMA-Motor
Fugl-Meyer Assessment motor domain
BI
Barthel Index
ECG
electrocardiography
HRV
heart rate variability
RMSSD
root mean square of successive differences
SDNN
standard deviation of normal-to-normal intervals
BIC
Bayesian information criterion
NIHSS
National Institutes of Health Stroke Scale.

Declarations

Ethics approval and consent to participate

The study was approved by the Institutional Review Board of the Korea Institute for Health Affairs (IRB No. BS25Ga14586) before participant recruitment. All participants received written and verbal information about the study purpose and procedures, wearable-based data collection, potential discomforts, privacy protection, and their right to withdraw without disadvantage. Written informed consent was obtained from all participants before enrollment. Participants selected for the qualitative phase provided additional consent for audio recording and transcription of the interviews. The study was conducted in accordance with the principles of the Declaration of Helsinki.

Consent for publication

Not applicable. No identifiable individual participant information is presented in this manuscript.

Competing interests

The author declares no competing interests.

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Author Contribution

SK was responsible for conceptualization, methodology, investigation, data curation, formal analysis, visualization, interpretation of the findings, and preparation of the original manuscript. SK also reviewed and edited the manuscript and approved the final version.

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Data Availability

The datasets generated and/or analysed during the current study are not publicly available due to ethical and privacy restrictions associated with longitudinal clinical data, wearable-derived physiological and behavioral measurements, and qualitative interview transcripts, but are available from the corresponding author on reasonable request, subject to applicable ethical approvals and data protection requirements.

References

1. Langhorne, P., Coupar, F. & Pollock, A. Motor recovery after stroke: a systematic review. *Lancet Neurol.* **8**, 741–754. https://doi.org/10.1016/S1474-4422(09)70150-4 (2009).
2. Quinn, T. J., Langhorne, P. & Stott, D. J. Barthel index for stroke trials: development, properties, and application. *Stroke* **42**, 1146–1151. https://doi.org/10.1161/STROKEAHA.110.598540 (2011).
3. Cumming, T. B., Packer, M., Kramer, S. F. & English, C. The prevalence of fatigue after stroke: A systematic review and meta-analysis. *Int. J. Stroke*. **11**, 968–977. https://doi.org/10.1177/1747493016669861 (2016).

4. Fulk, G. D. et al. The Impact of Sleep Disorders on Functional Recovery and Participation Following Stroke: A Systematic Review and Meta-Analysis. *Neurorehabil Neural Repair.* **34**, 1050–1061. https://doi.org/10.1177/1545968320962501 (2020).
5. Chen, T. et al. Long-term unmet needs after stroke: systematic review of evidence from survey studies. *BMJ Open.* **9**, e028137. https://doi.org/10.1136/bmjopen-2018-028137 (2019).
6. Obembe, A. O. & Eng, J. J. Rehabilitation Interventions for Improving Social Participation After Stroke: A Systematic Review and Meta-analysis. *Neurorehabil Neural Repair.* **30**, 384–392. https://doi.org/10.1177/1545968315597072 (2016).
7. Aftyka, J., Staszewski, J., Dębiec, A., Pogoda-Wesołowska, A. & Żebrowski, J. Heart rate variability as a predictor of stroke course, functional outcome, and medical complications: A systematic review. *Front. Physiol.* **14**, 1115164. https://doi.org/10.3389/fphys.2023.1115164 (2023).
8. Luo, Y., Yu, G., Liu, Y., Zhuge, C. & Zhu, Y. Sleep quality after stroke: A systematic review and meta-analysis. *Med. (Baltim).* **102**, e33777. https://doi.org/10.1097/MD.0000000000033777 (2023).
9. Barkhudaryan, A., Doehner, W. & Jauert, N. Autonomic dysfunction after stroke: an overview of recent clinical evidence and perspectives on therapeutic management. *Clin. Auton. Res.* **35**, 553–563. https://doi.org/10.1007/s10286-025-01120-0 (2025).
10. English, C., Manns, P. J., Tucak, C. & Bernhardt, J. Physical activity and sedentary behaviors in people with stroke living in the community: a systematic review. *Phys. Ther.* **94**, 185–196. https://doi.org/10.2522/ptj.20130175 (2014).
11. Rand, D., Eng, J. J., Tang, P-F., Jeng, J-S. & Hung, C. How active are people with stroke? use of accelerometers to assess physical activity. *Stroke* **40**, 163–168. https://doi.org/10.1161/STROKEAHA.108.523621 (2009).
12. Demers, M. et al. Wearable Technology to Capture Arm Use of People With Stroke in Home and Community Settings: Feasibility and Early Insights on Motor Performance. *Phys. Ther.* **104**, pzad172. https://doi.org/10.1093/ptj/pzad172 (2024).
13. Lohse, K. R., Miller, A. E., Bland, M. D., Lee, J-M. & Lang, C. E. Association Between Real-World Actigraphy and Poststroke Motor Recovery. *Stroke* **56**, 2079–2090. https://doi.org/10.1161/STROKEAHA.124.050229 (2025).
14. Bernaldo de Quirós, M., Douma, E. H., van den Akker-Scheek, I., Lamoth, C. J. C. & Maurits, N. M. Quantification of Movement in Stroke Patients under Free Living Conditions Using Wearable Sensors: A Systematic Review. *Sens. (Basel) Basel Switz.* **22**, 1050. https://doi.org/10.3390/s22031050 (2022).
15. Toh, S. F. M., Fong, K. N. K., Gonzalez, P. C. & Tang, Y. M. Application of Home-Based Wearable Technologies in Physical Rehabilitation for Stroke: A Scoping Review. *IEEE Trans. Neural Syst. Rehabil Eng.* **31**, 1614–1623. https://doi.org/10.1109/TNSRE.2023.3252880 (2023).
16. Lou, S., Carstensen, K., Jørgensen, C. R. & Nielsen, C. P. Stroke patients' and informal carers' experiences with life after stroke: an overview of qualitative systematic reviews. *Disabil. Rehabil*. **39**, 301–313. https://doi.org/10.3109/09638288.2016.1140836 (2017).

17. Woodman, P., Riazi, A., Pereira, C. & Jones, F. Social participation post stroke: a meta-ethnographic review of the experiences and views of community-dwelling stroke survivors. *Disabil. Rehabil*. **36**, 2031–2043. https://doi.org/10.3109/09638288.2014.887796 (2014).
18. Northcott, S., Moss, B., Harrison, K. & Hilari, K. A systematic review of the impact of stroke on social support and social networks: associated factors and patterns of change. *Clin. Rehabil*. **30**, 811–831. https://doi.org/10.1177/0269215515602136 (2016).
19. Lo, T. L. T., Lee, J. L. C. & Ho, R. T. H. Recovery beyond functional restoration: a systematic review of qualitative studies of the embodied experiences of people who have survived a stroke. *BMJ Open.* **13**, e066597. https://doi.org/10.1136/bmjopen-2022-066597 (2023).
20. Shalabi, K. M., Mahmoud, H., Pakkir Mohamed, S. H. & Shaik, S. A. Digital biomarkers derived from wearable sensors in neurorehabilitation: a scoping review. *Front. Neurol.* **17**, 1908796. https://doi.org/10.3389/fneur.2026.1908796 (2026).
21. Duffy, L., Gajree, S., Langhorne, P., Stott, D. J. & Quinn, T. J. Reliability (inter-rater agreement) of the Barthel Index for assessment of stroke survivors: systematic review and meta-analysis. *Stroke* **44**, 462–468. https://doi.org/10.1161/STROKEAHA.112.678615 (2013).
22. Gladstone, D. J., Danells, C. J. & Black, S. E. The fugl-meyer assessment of motor recovery after stroke: a critical review of its measurement properties. *Neurorehabil Neural Repair.* **16**, 232–240. https://doi.org/10.1177/154596802401105171 (2002).
23. Kim, T-L. et al. The Korean Version of the Fugl-Meyer Assessment: Reliability and Validity Evaluation. *Ann. Rehabil Med.* **45**, 83–98. https://doi.org/10.5535/arm.20225 (2021).
24. Lee, Y. J., Lee, J. Y., Cho, J. H., Kang, Y. J. & Choi, J. H. Performance of consumer wrist-worn sleep tracking devices compared to polysomnography: a meta-analysis. *J. Clin. Sleep. Med.* **21**, 573–582. https://doi.org/10.5664/jcsm.11460 (2025).
25. Carter, J. R. et al. Guidelines for rigor and reproducibility of heart rate variability within human cardiovascular research. *Am. J. Physiol. Heart Circ. Physiol.* **331**, H918–H943. https://doi.org/10.1152/ajpheart.00041.2026 (2026).
26. Quigley, K. S. et al. Publication guidelines for human heart rate and heart rate variability studies in psychophysiology-Part 1: Physiological underpinnings and foundations of measurement. *Psychophysiology* **61**, e14604. https://doi.org/10.1111/psyp.14604 (2024).
27. Braun, V. & Clarke, V. A critical review of the reporting of reflexive thematic analysis in Health Promotion International. *Health Promot Int.* **39**, daae049. https://doi.org/10.1093/heapro/daae049 (2024).
28. Vratsistas-Curto, A., Downie, A., McCluskey, A. & Sherrington, C. Trajectories of arm recovery early after stroke: an exploratory study using latent class growth analysis. *Ann. Med.* **55**, 253–265. https://doi.org/10.1080/07853890.2022.2159062 (2023).
29. Orange, C. et al. Determinants of Return to Work After a Stroke: A Systematic Review and Meta-analysis. *Arch. Phys. Med. Rehabil*. **105**, 359–368. https://doi.org/10.1016/j.apmr.2023.08.027 (2024).

30. Fuller, D. et al. Reliability and Validity of Commercially Available Wearable Devices for Measuring Steps, Energy Expenditure, and Heart Rate: Systematic Review. *JMIR Mhealth Uhealth*. **8**, e18694. https://doi.org/10.2196/18694 (2020).
31. Green, T. L. et al. Care of the Patient With Acute Ischemic Stroke (Posthyperacute and Prehospital Discharge): Update to 2009 Comprehensive Nursing Care Scientific Statement: A Scientific Statement From the American Heart Association. *Stroke* **52**, e179–e197. https://doi.org/10.1161/STR.0000000000000357 (2021).

Figures

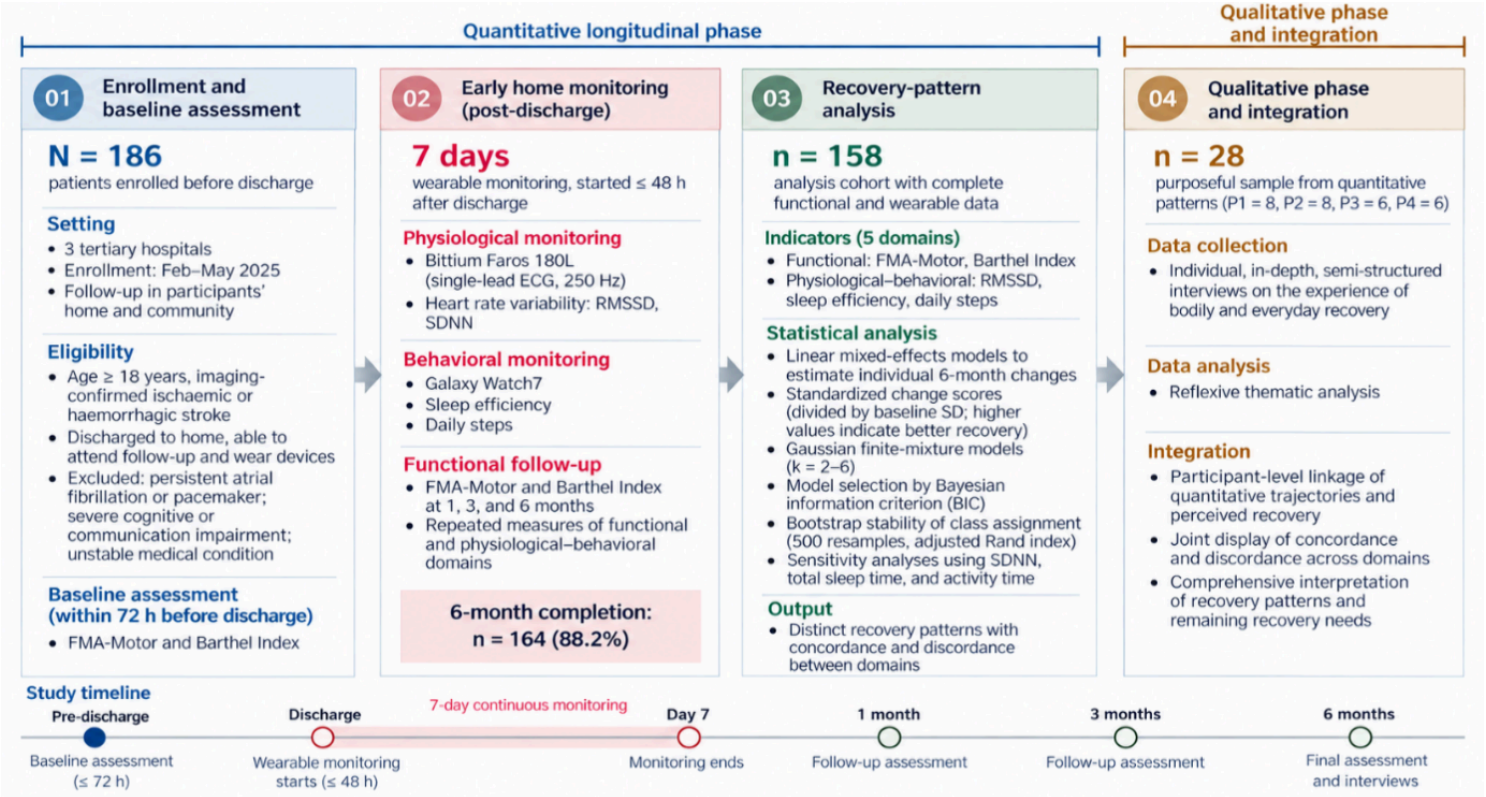


Figure 1

Study design and mixed-methods integration

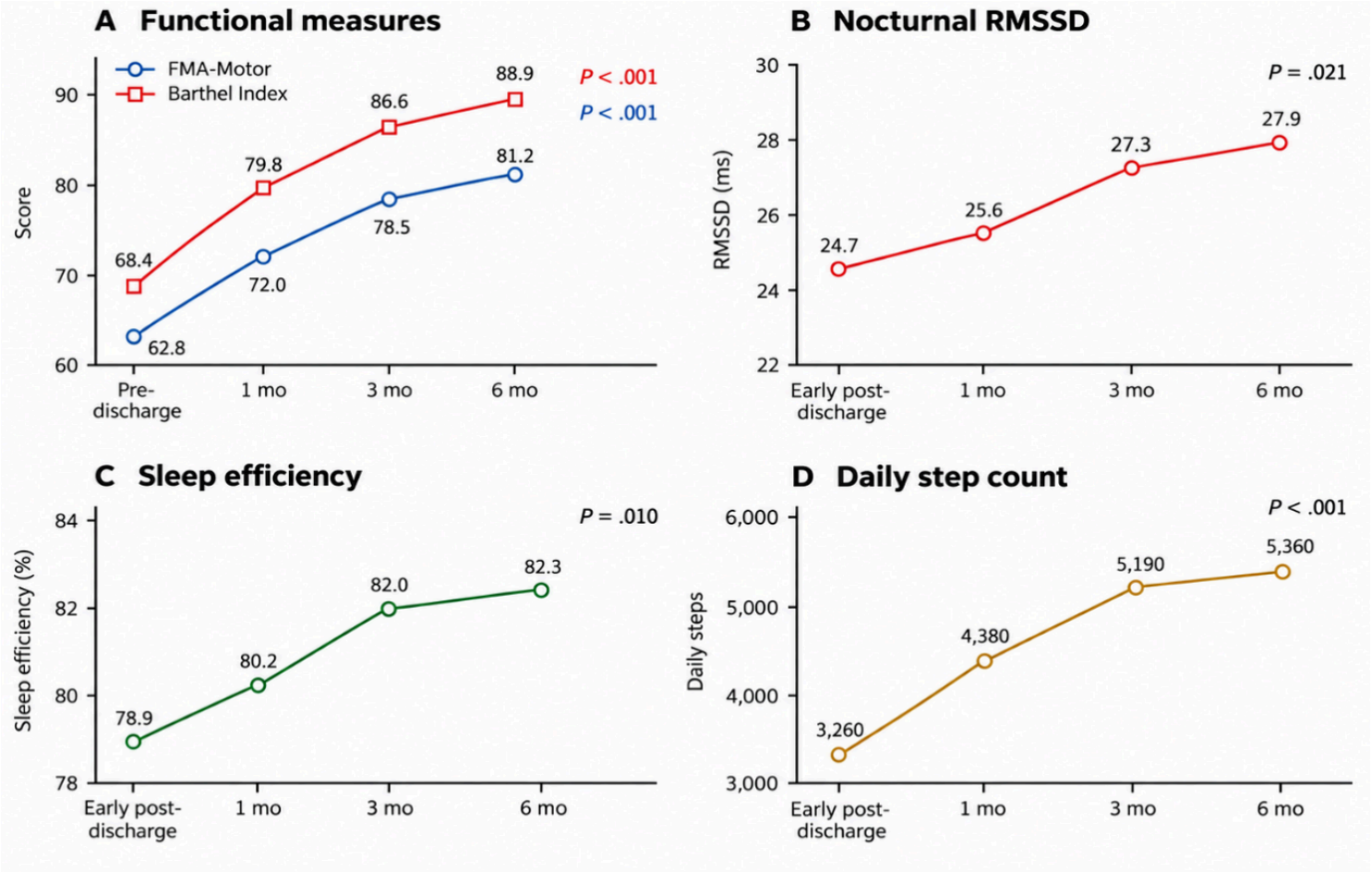


Figure 2

Group-Level Longitudinal Changes in Functional and Wearable-Derived Recovery Measures

Note. Points represent observed summary values at each assessment point (means for FMA-Motor, Barthel Index, and sleep efficiency; medians for RMSSD and daily steps). p values indicate the overall effect of time from linear mixed-effects models adjusted for study site. The number of available observations varied across follow-up points. RMSSD and daily steps were log-transformed for model-based inference. FMA-Motor, Fugl–Meyer Assessment motor domain; RMSSD, root mean square of successive differences.

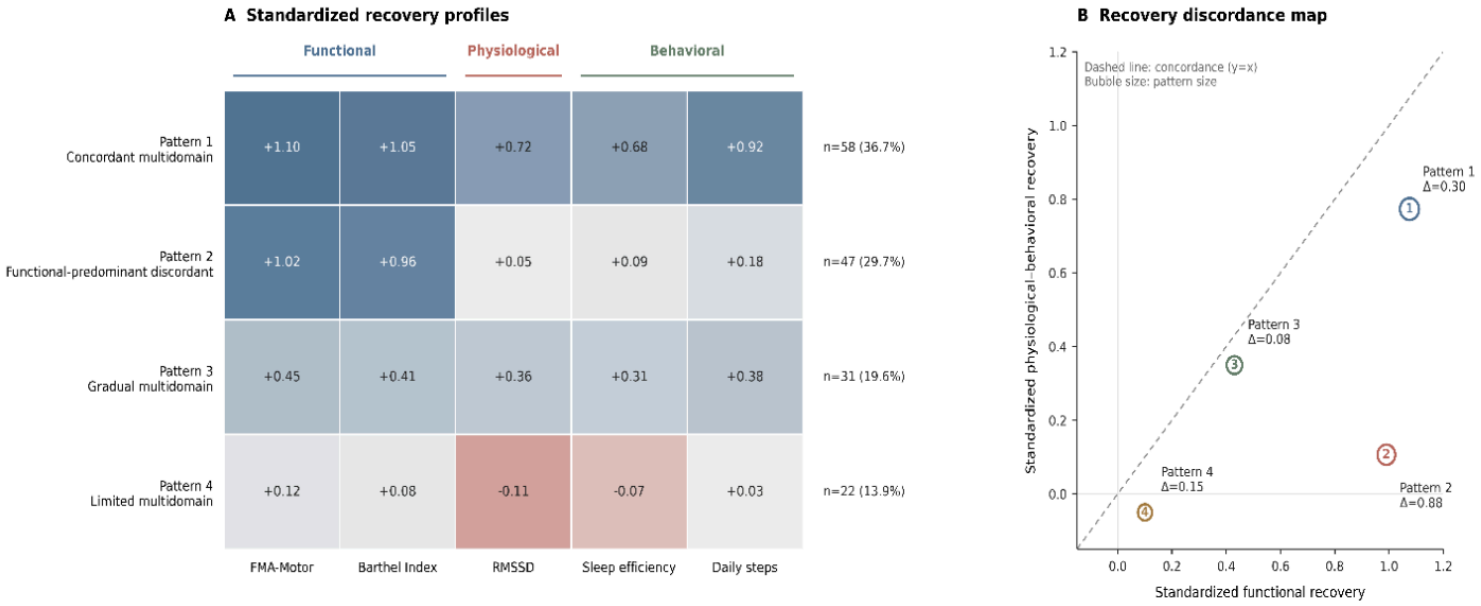


Figure 3

Recovery patterns and discordance between functional and physiological–behavioral recovery

Note. Panel A shows mean standardized model-estimated changes from each measure's corresponding baseline to the 6-month follow-up within the 4 recovery patterns; 0 indicates no change and positive values indicate change in the direction of better recovery. Standardized functional recovery in Panel B is the mean of FMA-Motor and Barthel Index change scores, whereas standardized physiological–behavioral recovery is the mean of RMSSD, sleep efficiency, and daily step change scores. The dashed line represents concordance between the two domain-level summaries (y = x). Δ was calculated as standardized functional recovery minus standardized physiological–behavioral recovery and is descriptive; cluster classification was based on the full five-variable profile rather than on a prespecified Δ threshold. Bubble size is proportional to the number of participants in each pattern. FMA-Motor = Fugl–Meyer Assessment motor domain; RMSSD = root mean square of successive differences.

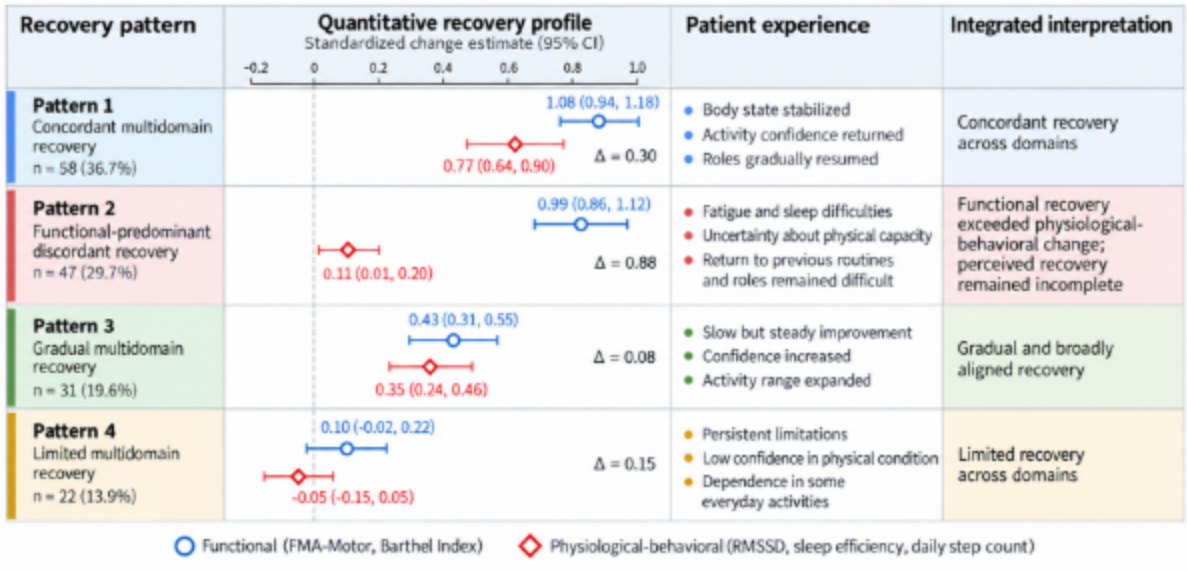


Figure 4

Mixed-methods joint display of recovery patterns and patient-perceived recovery

Note. Functional recovery represents the mean standardized model-estimated change from the pre-discharge assessment to 6 months in FMA-Motor and the Barthel Index, whereas physiological-behavioral recovery represents the mean standardized model-estimated change from the initial postdischarge monitoring period to 6 months in RMSSD, sleep efficiency, and daily step count. Points indicate pattern-level mean standardized change estimates, and horizontal whiskers indicate 95% confidence intervals estimated using within-pattern nonparametric bootstrap resampling. Δ was calculated as functional recovery minus physiological-behavioral recovery; larger positive values indicate greater between-domain divergence. Δ values were calculated from unrounded domain-level estimates. These domain-level summaries were used only to visualize and interpret the integrated findings and were not used to derive the recovery-pattern clusters. Patient-perceived recovery summarizes pattern-specific experiences identified through qualitative interviews. FMA-Motor, Fugl-Meyer Assessment motor domain; RMSSD, root mean square of successive differences.

Supplementary Files

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- SupplementaryMaterial04.docx