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Recovery of unilateral and bilateral upper extremity capacity and proprioception after stroke: A longitudinal study using robotic assessment

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Abstract

Background

Recovery after stroke is characterised by substantial inter-individual variability and can differ across impairment domains. Current knowledge of upper-extremity (UE) recovery is largely based on unilateral motor assessments. However, most activities of daily living (ADLs) require bilateral UE use. Moreover, proprioceptive impairments may follow distinct recovery trajectories compared with motor deficits and could influence the recovery of bilateral capacity. This study aimed to characterize and compare the recovery of different sensorimotor impairments during the subacute phase, using unilateral, bilateral, and proprioceptive robotic tasks.

Methods

Participants (n = 41) were assessed using the KINARM Exoskeleton Lab at three time points: admission to inpatient rehabilitation, prior to discharge, and six months post-stroke. Participants performed a unilateral task (Visually Guided Reaching), a bilateral task (Ball on Bar), and a proprioceptive task (Arm Position Matching), as well as a clinical assessment of performance in ADLs (CAHAI). For each robotic task, a Z-score based on normative data was calculated. Linear mixed models were used to assessed changes over time and associations between assessments.

Results

Improvement was observed in all robotic assessments ($p \leq 0.01$), with most of the improvement occurring during the rehabilitation period. Recovery trajectories across tasks followed different patterns in 40% to 53% of participants, with the largest differences observed between motor and proprioceptive tasks. Linear mixed models indicated a significant between-subject effect across all tasks, whereas a significant within-subject effect was only observed between unilateral and bilateral tasks, indicating independent recovery trajectories between motor and proprioceptive domains. Unilateral capacity, bilateral capacity, and proprioception were all independent contributors to ADL performance, with bilateral capacity showing the strongest contribution.

Background

Recovery after stroke is characterised by substantial variability in both the timing and extent of recovery between individuals (1, 2, 3). However, it remains unclear whether different impairment domains follow distinct recovery trajectories or recover in parallel (4, 5, 6, 7, 8, 9). Improving our understanding of recovery across specific domains has been identified as a key priority in stroke research, as it provides a foundation for precision rehabilitation approaches (10).

Current knowledge of upper-extremity (UE) recovery is largely derived from unilateral motor assessments (11). However, most activities of daily living (ADLs) require the use of both UE, and stroke survivors mostly use their affected UE in the context of bimanual activities (12, 13). Although impairments in interlimb coordination have been well documented in chronic stroke populations (14), evidence remains limited regarding recovery of bilateral capacity during the subacute phase. The few studies comparing recovery of unilateral and bilateral UE capacity reported inconsistent findings, ranging from strong association between domains and similar recovery trajectories (15), to inconsistencies in timing of recovery at the individual-level (8), and reduced kinematic quality during bilateral compared with unilateral reaching across the subacute phase (16). However, these findings are difficult to interpret, as studies have used non-comparable measures across domains (e.g., impairment- vs. activity-level clinical scales) (15), tasks with substantially different demands (e.g., reaching static vs. moving targets) (8), or have not directly compared recovery trajectories (16). Consequently, it remains unclear whether unilateral and bilateral motor capacities recover in parallel or follow distinct trajectories over time.

Additionally, factors that may contribute to differences in recovery between unilateral and bilateral capacities should be considered. Somatosensory impairment has been associated with deficits in bilateral capacity after stroke, with proprioception specifically linked to interlimb coordination and limitations in bimanual activities (17, 18, 19). Proprioceptive deficits are common following stroke (20, 21), and evidence suggests that motor and proprioceptive recovery follow distinct trajectories (8). This supports the need to characterize and compare the recovery of both proprioception and bilateral capacity during the subacute phase after stroke.

Robotic platforms enable assessment of UE kinematics across unilateral, bilateral, and proprioceptive tasks within a standardised and unified framework, thereby facilitating direct comparison of recovery across domains (20, 22, 23). This approach addresses key limitations of previous recovery studies relying on ordinal clinical scales, which are prone to floor and ceiling effects and limited sensitivity to change (2, 24). By providing continuous and objective measures of movement quality, robotic kinematic assessments offer a more precise characterization of sensorimotor recovery (25).

The aim of this longitudinal study was to characterize and compare the recovery of sensorimotor capacity during the subacute phase following stroke using unilateral, bilateral and proprioceptive robotic tasks. Specifically, we sought to (1) quantify changes in sensorimotor capacity over time; (2) compare impairment and recovery trajectories across unilateral, bilateral, and proprioceptive domains; (3) identify determinants of bilateral capacity; and (4) examine how these capacities relate to performance in ADLs.

Methods

Study design and participants

Admissions to a stroke rehabilitation unit at the Quebec Physical Rehabilitation Institute were systematically screened for eligibility between May 2022 and December 2024. Participants were

approached to participate if they met the following inclusion criteria: 1) diagnosis of ischemic or hemorrhagic stroke confirmed by a neurologist; 2) less than six weeks post-stroke at the time of consent; 3) presence of hemiparesis affecting the UE (i.e., weakness on manual muscle testing documented in the medical chart). Exclusion criteria included: 1) inability to follow verbal instructions; 2) previous symptomatic stroke or other neurological conditions; 3) pre-existing musculoskeletal condition affecting the UE. All participants written informed consent prior to participation. The study was approved by the hospital ethic board (CIUSSS-CN, #2022–2550).

Clinical and demographic information were extracted from medical records to characterize the sample. Cognitive function was assessed using the Montreal Cognitive Assessment (MoCA), depressive symptoms using the Patient Health Questionnaire (PHQ-9), and visuospatial neglect using the Bells Test (26, 27). Presence of visuospatial neglect was determined according to normative data reported by Mancuso et al. (28). These assessments were administered by the unit's neuropsychologist at admission.

Assessments were carried out at three different time points during the subacute phase: upon admission to the stroke rehabilitation unit (T1); six week later, prior to discharge (T2); at six months post-stroke (T3). All participants received intensive inpatient rehabilitation between admission and discharge, over a minimum period of six weeks. Rehabilitation consisted of four one-hour sessions of occupational therapy and four one-hour sessions of physical therapy per week. Additional interventions, such as task-specific group programs (e.g., Graded Repetitive Arm Supplementary Program (GRASP), gait and balance training) and speech therapy, were provided based on individual needs.

Robotic assessments

Unilateral and bilateral capacity and proprioceptive impairment were assessed using the Kinarm Exoskeleton Lab (Kinarm, Kingston, Ontario). Participants were seated in a height-adjustable chair with both arms supported by the exoskeleton at approximately 85° of shoulder abduction. Articulation at the shoulder and elbow allowed for movements in the horizontal plane. Vision of the participant arms was occluded, and task-related stimuli were displayed on a semi-reflective screen positioned in front of the participant. Figure 1 shows a representation of the experimental setup and an example of the visual display for each task.

Participants completed three Kinarm Standard tasks. To assess unilateral and bilateral motor capacity, two reaching tasks were administered: the Visually Guided Reaching task (VGR) (22), performed unilaterally, and the Ball on Bar task (BoB) (23), performed bilaterally. Proprioception was assessed using the Arm Position Matching task (APM) (20). Tasks were administered in the following order: VGR, BoB, and APM.

For each task, multiple kinematic parameters are obtained. Each parameter is converted to a standardized z-score based on age, sex, and limb dominance using a normative model derived from

healthy controls. To quantify the overall performance for each task, a composite z-task score is obtained by combining the task-specific parameters. A z-task score ≥ 1.65 is considered indicative of impairment, corresponding to a performance below the 5th percentile of the healthy control distribution. The detailed description of the process for z-score calculation of task-specific parameter and the z-task score is available in Simmatis et al. (29).

The VGR is a unilateral reaching task where the individual is instructed to reach five different targets with speed and precision. The targets are displayed as red circles (2 cm radius) arranged around a central target, with the four peripheral targets distributed on a circle of 10 cm radius. Targets appear in a pseudo-random sequence, requiring a total of 48 reaching movements (24 center-out and 24 center-in). Visual feedback of the arm position is provided as a white dot corresponding to the tip of the index finger. The task was performed with each arm separately, beginning with the non-paretic UE (VGRnp) followed by the paretic UE (VGRp). The task-specific parameters used to compute the task score are detailed in Coderre et al. (22).

The BoB is a bilateral reaching task with the added requirement of coordinating the movements of both UE. The participant uses both hands to maintain a virtual horizontal bar while keeping a ball balanced in its center. A force field is applied to maintain both hands in equal distance through the task and recreate an impression of holding the bar between hands. The participant is instructed to reach four targets with the ball, while preventing the ball from falling. The task consists of three levels with increasing difficulty. At level one, the ball remains fixed at the center of the bar regardless of tilt. At level two, the ball moves proportionally to the tilt of the bar. At level three, the ball moves and accelerates based on the tilt. The task-specific parameters used to compute the task score are detailed in Lowrey et al. (23).

The APM is a proprioceptive task assessing the ability to replicate limb positions without visual feedback. The exoskeleton passively moves the paretic arm to a specific position, and the participant is instructed to match this position with his non-paretic arm. The target positions are located in four locations corresponding to the corners of a square (20 cm per side). A total of 24 matching trials is performed. The task-specific parameters used to compute the task score are detailed in Dukelow et al. (20).

Performance in ADLs

Performance in ADLs was assessed using the Chedoke Arm and Hand Activity Inventory (CAHAI) (30). The CAHAI is a standardized and validated measure comprising nine bimanual functional tasks: 1) open a jar of coffee; 2) call 911; 3) draw a line with a ruler; 4) pour a glass of water; 5) wring out a washcloth; 6) fasten five buttons; 7) dry the back with a towel; 8) put toothpaste on a toothbrush; 9) cut medium-consistency putty with a knife and fork. Each task is scored using a seven-level ordinal scale reflecting the use of the paretic UE, ranging from total dependence to complete independence. Total scores range from 9 to 63, with higher scores indicating better performance.

Analysis

Descriptive statistics were computed to characterize the sample at baseline, with means and standard deviations reported for continuous variables and frequencies for categorical variables.

All analyses were conducted in R version 4.3.0. Linear mixed models (LMMs) were used to assess change over time and longitudinal associations between assessments with the *lme4* R package (31). All models included a random intercept for subjects to account for inter-individual variability in baseline capacity. All continuous covariates were standardised prior to analysis, and results were reported as standardised regression coefficients (β) ± standard error (SE) with 95% confidence intervals. Marginal R^2, describing the proportion of variance explained by the fixed effects, were calculated following the Nakagawa & Schielzeth method using the *performance* R package (32). For all LMMs, model assumptions were checked using standard diagnostics for residuals, influential observations, and random effects (31, 33). Sensitivity analyses were run without potential influential observations to ensure models stability.

Changes in sensorimotor capacity over time

To assess changes over time, separate LMMs were fitted for each outcome with time entered as a three-level categorical fixed effect (T1, T2, T3). Post-hoc pairwise comparisons between time points were performed using estimated marginal means with Tukey adjustment for multiple comparisons, implemented via the *emmeans* R package (34).

Comparison of impairment and recovery trajectories across domains

Comparison at the individual level was done by classifying participants based on baseline impairment status (i.e., impaired vs non-impaired at T1) and recovery trajectories (i.e., improvement between T1 and T3) across all robotic tasks. Recovery was defined using one of two criteria: (1) participants who were impaired at T1 and whose z-score crossed below the impairment threshold ($z < 1.65$) at T3, or (2) participants whose change in z-score between T1 and T3 exceeded the threshold for significant change as defined by Simmatis et al. (29). For participants without a T3 assessment, T2 data were used as the endpoint. Comparisons between pairs of tasks then allowed to determine if a participant showed an inconsistent impairment status or recovery profile between two tasks (e.g., participant showing impairment in the VGR, but not in the BoB at T1, or showing recovery in the VGR, but not in the APM).

Group-level analyses were also carried out by assessing associations between the robotic tasks by using LMMs. Associations between bilateral and unilateral capacity was assessed by modeling the BoB as an outcome of the VGR. Associations between motor and proprioception was assessed by modeling the motor tasks (VGRp, BoB) as outcomes of the APM. In each model, time was included as a fixed effect as described above, and the covariate of interest was decomposed into between-subject and within-subject

components to dissociate associations driven by average impairment level from those reflecting within-individual change over time (35).

Determinants of bilateral capacity and performance in ADLs

LMMs were used to identify predictors of bilateral capacity (BoB) and of performance in ADLs (CAHAI). First, separate exploratory analyses were conducted to examine univariate associations between these two outcomes and demographic (age, sex) and baseline clinical variables (lesion side, dominant UE affected, cognition, neglect and depression). Variables with a $p < 0.10$ in the univariate analysis were retained for inclusion in the corresponding final model. For the model predicting bilateral capacity, fixed effects included Time and the following covariates: VGRp, VGRnp, APM, along with any demographic and clinical variables identified in the univariate analyses. For the models predicting performance in ADLs, fixed effects included Time and the following covariates: VGRp, VGRnp, BoB, APM, along with any demographic and clinical variables retained from the univariate analyses.

Results

A total of 41 stroke survivors were enrolled and assessed upon admission to the rehabilitation unit. Among the 209 admissions screened, 62 met the eligibility criteria and 41 consented to participate. Participants' demographic and clinical characteristics are summarized in Table 1. The sample size decreased to 38 participants at discharge, and to 32 at six months post-stroke. Attrition was due to voluntary withdrawal (n=3), transition to palliative care (n=2), inability to perform robotic assessment due to severe shoulder capsulitis (n=1), recurrent stroke (n=1), distance constraint (n=1), and inability to contact (n=1). Participants lost to follow-up did not differ significantly from those who completed the study in terms of baseline demographic variables, cognitive function, visuospatial neglect, CAHAI scores, and robotic outcomes. However, right hemisphere lesions were more frequent among participants lost to follow-up (p=0.02).

A few participants with severe UE paresis could not complete the BoB assessment at admission (n=6). For descriptive analyses based on an impaired vs. non-impaired categorization at baseline, these cases were retained and classified as impaired; however, they were treated as missing in the LMM models. Some participants with substantial shoulder pain and/or capsulitis did not perform the BoB (n=1 at T2, n=1 at T3) or the APM (n=2 at T1, T2, and T3) due to the possible risk related to passive movements at the shoulder produced by the exoskeleton. Neglect results were not available for three participants.

Table 1. Demographic and clinical information (n= 41)

	Mean (SD)
Age	64.6 (14.4)
Time since stroke (days)	
Admission (n=41)	28.4 (8.0)
Discharge (n=38)	67.9 (11.0)
6 months (n=32)	207.3 (25.4)
Days in rehabilitation	60.8 (25.8)
CAHAI at admission	33.5 (18.1)
MoCA	23.0 (4.2)
PHQ-9	5.9 (4.6)
	n (%)
Gender (Male/Female)	26/15 (63/37)
Side of lesion (Right/Left)	24/17 (58/42)
Type of stroke (Isch/Hem)	31/10 (76/24)
Dominant hand affected (Yes/No)	18/23(44/56)
Neglect (Yes/No)	11/27 (29/71)

Abbreviations: CAHAI, Chedoke Arm and Hand Activity Inventory, range 9-63; Hem, Hemorrhagic Stroke; Isch, Ischemic Stroke; MoCA, Montreal Cognitive Assessment, range 0–30; PHQ-9, Nine-item Patient Health Questionnaire, range 0-27.

Changes in sensorimotor capacity over time

Table 2 presents the percentage of subjects with an impairment (z-score ≥ 1.65) in each robotic task at different times of the subacute phase. Impairments in the unilateral task on the paretic side (VGRp) and in the bilateral task (BoB) were the most frequent at all time points, with similar proportions of impaired participants between the two tasks. A few participants showed impairment in their non-paretic UE in the VGR task, which remained present at 6-months post-stroke. Proprioceptive deficits (APM) were less frequent than motor deficits. At six months post-stroke, 23 of 32 participants (72%) remained impaired in at least one task.

Table 2. Proportion of impaired subjects in the robotic tasks

	Admission (n=41)	Discharge (n=38)	6 months (n=32)
VGR paretic	78.0%	57.9%	46.9%
VGR non-paretic	12.2%	10.5%	9.4%
BoB	78.0%	55.3%†	46.9%†
APM	56.4%‡	37.1%‡	23.3%‡

Abbreviations: VGR, Visually Guided Reaching; BoB, Ball on Bar; OH, Object Hit; APM, Arm Position Matching. † 1 subject with missing data; ‡ 2 subjects with missing data.

Changes in capacity over time during the subacute phase post-stroke are shown in Figure 2. A significant effect of time was observed in all robotic tasks ($p \leq 0.01$). Post-hoc analysis showed that most of the change were observed between admission and discharge, with no significant change between discharge and 6 months post-stroke for the VGRp, VGRnp, and APM, although a trend toward improvement was observed for the APM ($p=0.06$). However, significant improvement after discharge were observed for the BoB task ($p \leq 0.015$).

At the individual level, high variability in magnitude and timing of recovery can be observed between individuals, as depicted by the grey, green and red lines representing individual trajectories in Figure 2. Although group-level analyses revealed no significant changes between discharge and 6 months post-stroke for most robotic tasks, a small subset of participants showed significant change at the individual-level during this period.

Comparison of impairment and recovery trajectories across domains

Comparisons of within-individual impairment status (i.e., impairment at T1) and recovery trajectories (i.e., significant change between T1 and T3) across unilateral, bilateral and proprioceptive domains are presented in Figure 3.

A modest level of inconsistency in impairment status across tasks was observed. For example, at admission, five participants were impaired on the BoB task despite normal performance on the VGR task, whereas five others showed impaired VGR performance with preserved BoB performance (Figure 3A). Such inconsistent impairment status was observed across all task pairs, and it was more frequent between proprioceptive and motor tasks (36.1%) than between unilateral and bilateral tasks (26.3%).

Inconsistencies in recovery trajectories at the individual level were more pronounced and were also more frequent between proprioceptive and motor tasks (44.4-52.8%) than between unilateral and bilateral tasks (39.5%). Similar rates of recovery inconsistency were observed when analyses were restricted to participants who were impaired in both tasks at admission (41.2–47.1%).

These descriptive patterns were supported by the results of the linear mixed models, which quantified between- and within-subject associations across tasks (Table 3). A significant between-subject association was observed between unilateral and bilateral capacity (β=1.57; p<0.001), indicating that participants with better average unilateral capacity tended to show better bilateral capacity. Similarly, between-subject associations between proprioceptive and motor tasks were consistently significant (β =1.03-1.72; p<0.001).

Within-subject change in unilateral capacity was associated with improvements in bilateral capacity (β=0.23; p≤0.001). However, the within-subject effect was modest in magnitude when compared to the corresponding between-subject association in the same model. In contrast, within-subject change in proprioception was not associated with change in unilateral (p=0.62) or bilateral capacity (p=0.27), consistent with dissociable recovery trajectories between proprioceptive and motor capacity.

Table 3. Associations between sensorimotor domains

Association between unilateral and bilateral capacity

Outcome	Predictors	β ± SE	p-value	CI (95%)	Marginal R^2
BoB					0.607
	Constant	3.28±0.19	p<0.001*	2.91; 3.65	
	T1-T2	-0.77±0.17	p=0.001*	-1.09; -0.45	
	T1-T3	-1.18±0.20	p<0.001*	-1.56; -0.80	
	VGRp between	1.57±0.20	p<0.001*	1.18; 1.95	
	VGRp within	0.23±0.09	p=0.018*	0.04; 0.41	

Associations between motor capacity and proprioception

Outcome	Predictors	β ± SE	p-value	CI (95%)	Marginal R^2
VGRp					0.373
	Constant	5.35±0.50	p<0.001*	4.38; 6.32	
	T1-T2	-2.41±0.51	p<0.001*	-3.43; -1.42	
	T1-T3	-3.34±0.61	p<0.001*	-4.55; -2.16	
	APM between	1.72±0.41	p<0.001*	0.92; 2.52	
	APM within	0.12±0.24	p=0.624	-0.36; 0.59	
BoB					0.423
	Constant	3.11±0.22	p<0.001*	2.69; 3.54	
	T1-T2	-0.90±0.16	p<0.001*	-1.21; -0.59	
	T1-T3	-1.42±0.18	p<0.001*	-1.78; -1.06	
	APM between	1.03±0.07	p<0.001*	0.63; 1.44	
	APM within	0.09±0.21	p=0.268	-0.06; 0.23	

β ± SE, Standardized beta coefficients ± standard error

CI (95%), 95% confidence interval of the standardized beta coefficient

APM, Arm Position Matching; BoB, Ball on Bar; OH, Object Hit; VGRp, Visually Guided Reaching of the paretic UE

Determinants of bilateral capacity

Presence of neglect and lesion side were not significantly associated with bilateral capacity, but they were retained for the final model as they reached the threshold set for inclusion ($p<0.10$; Table 4).

Predictors of bilateral capacity are presented in Table 5. The model explained a substantial proportion of variance in bilateral capacity (marginal R^2=0.424). Contralesional unilateral capacity and proprioception contributed significantly to the model, with unilateral capacity having the largest effect. Ipsilesional unilateral capacity did not contribute to bilateral capacity (p=0.889).

Table 4. Univariate associations with demographical and clinical variables

	BoB		CAHAI	
Variable	**β ± SE**	**p-value**	**β ± SE**	**p-value**
Age	-0.12±0.26	p=0.640	1.7±2.5	p=0.496
Sex	0.76±0.53	p=0.162	-8.1±5.1	p=0.118
Lesion side	-0.99±0.52	p=0.065	5.0±5.1	p=0.331
Concordance	-0.59±0.53	p=0.270	1.8±5.1	p=0.731
MoCA	-0.28±0.28	p=0.332	3.6±2.5	p=0.167
Neglect	1.10±0.56	p=0.059	-7.3±5.5	p=0.192
PHQ-9	0.09±0.29	p=0.746	0.8±2.7	p=0.774

β ± SE, Standardized beta coefficients ± standard error

BoB, Ball on Bar; MoCA, Montreal Cognitive Assessment; PHQ9, Nine-item Patient Health Questionnaire.

Table 5. Predictors of bilateral capacity

Outcome	Predictors	β ± SE	p-value	CI (95%)	Marginal R^2
BoB					0.424
	Constant	2.93±0.31	p<0.001*	2.34; 3.54	
	T1-T2	-0.59±0.17	p=0.001*	-0.92; -0.22	
	T1-T3	-0.81±0.22	p<0.001*	-1.24; -0.35	
	VGRp	0.60±0.14	p<0.001*	0.31; 0.92	
	VGRnp	0.01±0.10	p=0.889	-0.18; 0.21	
	APM	0.38±0.14	p=0.006*	0.12; 0.66	
	Neglect	0.30±0.44	p=0.496	-0.53; 1.16	
	Lesion side	-0.42±0.40	p=0.300	-1.20; 0.34	

β ± SE, Standardized beta coefficients ± standard error

CI (95%), 95% confidence interval of the standardized beta coefficient

APM, Arm Position Matching; BoB, Ball on Bar; VGRnp, Visually Guided Reaching of the non-paretic UE; VGRp, Visually Guided Reaching of the paretic UE.

Predictors of performance in ADLs

The linear mixed model assessing predictors of performance on the CAHAI is presented in Table 6. The model explained a substantial proportion of variance in ADLs performance (marginal R^2=0.613). Bilateral capacity was the strongest contributor to the model (β=-6.31±1.45; p<0.001), followed by contralesional unilateral capacity (β=-5.61±1.29; p<0.001). Ipsilesional unilateral capacity and proprioception also contributed significantly to the model, although they explained comparatively little unique variance. No demographic and baseline clinical covariates were included in the final model as they showed no significant association with performance in ADL (Table 4).

Table 6. Predictors of performance in ADLs

Outcome	Predictors	β ± SE	p-value	CI (95%)	Marginal R^2
CAHAI					0.613
	Constant	41.77±1.69	p<0.001*	38.5; 45.0	
	T1-T2	-0.31±1.41	p=0.828	-3.0; 2.4	
	T1-T3	-0.13±1.74	p=0.941	-3.5; 3.2	
	VGRp	-5.61±1.29	p<0.001*	-8.1; -3.1	
	VGRnp	-1.53±0.76	p=0.049*	-3.0; -0.03	
	APM	-2.32±1.15	p=0.048*	-4.5; -0.1	
	BoB	-6.31±1.45	p<0.001*	-9.1; -3.5	

β ± SE, Standardized beta coefficients ± standard error

CI (95%), 95% confidence interval of the standardized beta coefficient

APM, Arm Position Matching; BoB, Ball on Bar; OH, Object Hit; VGR, Visually Guided Reaching of the paretic UE.

Discussion

The aim of this study was to characterize and compare the recovery of sensorimotor capacity during the subacute phase post-stroke using unilateral, bilateral and proprioceptive robotic tasks. Our findings indicates that unilateral and bilateral capacity and proprioception follow partially distinct recovery trajectories and that they provide complementary information about everyday function. We also demonstrate the impact of proprioceptive impairment on bilateral capacity post-stroke. These results highlight the complex and multidimensional nature of UE recovery and underscore the importance of assessing complementary aspects of sensorimotor domains.

Changes in sensorimotor capacity over time

Sensorimotor capacity improved substantially during the early subacute phase, corresponding to the period of inpatient rehabilitation. However, bilateral capacity continued to improve during the late subacute phase, indicating a more prolonged recovery process in this domain. This may reflect increasing engagement in real-world bimanual activities as individuals advance through the subacute phase (13), which may reinforce bilateral capacity through experience-dependent plasticity beyond the rehabilitation period.

Previous work using the Adult Assisting Hand Assessment Stroke have showed significant improvement in bilateral capacity up to six months post-stroke with a plateau between six months and one year post stroke (15, 19). However, these studies did not differentiate changes occurring during the early versus

late subacute phases. In addition, a study looking at kinematic of bilateral reaching reported a plateau in improvement as early as six weeks post-stroke (16). In contrast, our results demonstrate continued improvements during both early and late subacute phases, providing more precise characterization of the temporal dynamics of recovery of bilateral capacity.

Examination of individual trajectories revealed substantial inter-individual variability in both the magnitude and timing of recovery. This aligns with previous studies reporting that while most UE sensorimotor recovery occurs during the early subacute phase, trajectories are highly heterogeneous, with individuals exhibiting prolonged improvements extending into the late subacute or even chronic phases (1, 3, 8, 36). Taken together, these results demonstrate potential for continued recovery beyond the traditional rehabilitation window.

Differences in impairment and recovery across unilateral and bilateral capacity

The unilateral and bilateral tasks both consisted of reaching toward static targets, with the bilateral task having the additional requirement of coordinated movements of both UE. Deficits in interlimb coordination during cooperative bilateral tasks are well documented in chronic stroke (37), and studies have shown reduced kinematic quality during bilateral compared to unilateral reaching (16, 38). This added complexity may explain why some participants exhibited isolated impairment in the bilateral task, reflecting preserved reaching ability but impaired interlimb coordination.

However, a similar proportion of participants were impaired in both the unilateral and bilateral tasks, and inconsistencies in impairment status were evenly distributed, with as many participants impaired only in the unilateral task as in the bilateral task. These results align with studies reporting no significant differences between unimanual and bimanual reaching kinematics (39, 40). In addition, some studies have also described facilitation during bilateral movements, characterized by increased peak acceleration and velocity of the paretic UE in bilateral condition (41, 42). However, the presence and magnitude of such facilitation appear highly variable across individuals post-stroke (43). This facilitation through bimanual coupling may partly explain why a subset of participants performed better in the bilateral than in the unilateral task.

Despite these observations, inconsistent impairment status between unilateral and bilateral capacity remained relatively limited, affecting only about a quarter of the cohort. In addition, the significant between-subject effect indicates that participants with better average unilateral capacity tended to present better bilateral capacity. This aligns with previous evidence showing constant and strong associations between unilateral impairment and bimanual capacity at different time point during the subacute phase after stroke (15). Therefore, despite some task-related heterogeneity, impairment remains largely consistent across domains, supporting a strong link between unilateral and bilateral capacity.

However, a substantially larger proportion of participants showed inconsistencies in recovery trajectories across unilateral and bilateral capacity, and a significant but small within-subject effect was observed

between tasks. This suggests a partial coupling of recovery between unilateral and bilateral capacity. This reinforces previous evidence of within-individual differences in timing of recovery between unilateral and bilateral tasks during the subacute phase (8). One potential explanation of this decoupling in recovery could be related to specificity of motor learning. Evidence from healthy individuals indicates limited generalization of motor learning from unimanual to bimanual contexts (44, 45, 46, 47). Therefore, differences in rehabilitation exposure, such as a predominance of unimanual versus bimanual training, may contribute to domain-specific recovery patterns.

Differences in impairment and recovery across motor capacity and proprioception

Greater heterogeneity in impairment status and recovery trajectories was observed between motor and proprioceptive domains. While participants with better average proprioceptive function tended to demonstrate better unilateral and bilateral capacity, improvements in proprioception over time was not associated with improvement in motor capacity. Accordingly, 44–53% of participants exhibited discordant recovery patterns between proprioceptive and motor domains.

Associations between proprioceptive and motor impairments have been reported repeatedly in stroke populations (48). However, examination of individual profiles reveals a more complex picture. Previous studies have shown mismatch in impairment profiles in 38% of participants (49) and inconsistent recovery trajectories in 32–42% of stroke survivors across motor and proprioceptive domains (8, 9). In addition, significant between-subject associations, without corresponding within-subject relationships over time, have also been reported when assessing recovery of motor and somatosensory impairments (50). These findings align with our results, suggesting that although levels of impairments in motor and proprioceptive domains are related at the group level, their recovery trajectories are not coupled. This partial independence indicate that motor and proprioceptive recovery may be driven by different processes, potentially reflecting differences in the underlying neural substrates of motor and proprioceptive functions, which, while overlapping, also involve distinct neural structures (51, 52, 53, 54).

Predictor of bilateral capacity

Bilateral capacity was primarily predicted by contralesional unilateral capacity, with an additional and independent contribution of proprioception. Similarly, prior studies examining predictors of bilateral capacity have identified contributions of somatosensory impairment, such as stereognosis and touch discrimination, in addition of UE motor impairment and stroke severity (15, 19). Our findings further support the importance of somatosensory function for bilateral capacity, demonstrating that proprioception contributes uniquely to bilateral capacity beyond motor impairments.

In contrast, ipsilesional impairment did not significantly contribute to performance in the bilateral task. Although ipsilesional deficits have been proposed to influence bimanual coordination after stroke (55), their impact may be secondary compared to contralesional motor impairment and somatosensory deficits.

Performance in ADLs

Performance in ADLs was best explained by a combination of contralesional unilateral capacity and bilateral capacity. Ipsilesional unilateral capacity and proprioception also contributed significantly, although to a lesser extent. While the association between UE motor capacity and ADL performance is well established (56, 57), the additional and unique contribution of bilateral capacity underscores its importance for daily activities. This finding reinforces previous evidence linking bilateral capacity to independence in ADLs, as measured with the FIM and the Bartel Index (58, 59, 60). Moreover, bilateral capacity was the predictor with the higher standardised beta, suggesting that cooperative, goal-directed bilateral actions may capture demands of real-world function that are not fully reflected by unilateral capacity alone. This greater relative contribution of bilateral capacity is consistent with the high prevalence of bimanual UE use during the subacute stage of stroke recovery (13).

Previous studies have also reported associations between proprioception and ADL performance and general autonomy (21, 49, 61, 62), although these studies did not control for motor capacity. This distinction is important, as recent evidence indicates that somatosensory deficits may no longer predict functional outcomes once acute motor impairments are accounted for (63). In contrast, our findings demonstrate that proprioception remains a significant contributor of ADL performance, as it explains additional variance beyond both unilateral and bilateral UE motor capacity.

Implication for stroke rehabilitation and research

These findings underscore the importance of assessing different domains of UE sensorimotor capacity, as they may follow distinct recovery trajectories and provide complementary information about everyday function. Such comprehensive assessment may help clinicians identify distinct impairment profiles and tailor personalized rehabilitation strategies more effectively. In the context of time and resource constraints faced in clinical settings, robotic assessments offer a promising solution by enabling the efficient and standardized evaluation of a broad range of functionally relevant sensorimotor capacities.

Our findings also have implications for clinical trial design. First, they highlight the importance of selecting domain-specific outcome measures aligned with the targeted intervention, as different assessments capture partially distinct aspects of recovery and may influence observed trajectories, thereby impacting trial outcomes (64, 65). Second, they support the use of patient stratification based on impairment profiles to better match interventions to individual deficits, which may enhance treatment efficacy and statistical power (10). For example, inconsistent findings in trials comparing unimanual and bimanual interventions may partly reflect heterogeneity in recovery and inadequate outcome selection, as most trials of bimanual training have relied on unilateral assessments only (66). Therefore, incorporating objective measures of unilateral and bilateral capacity could improve both stratification (e.g., predominance of unilateral vs. bilateral deficits) and sensitivity for detecting changes.

Limitations

An important limitation was the dropout rate and the missing robotic data for some tasks in a subset of participants, resulting in 12.6% of the total possible task scores being unavailable. However, the linear mixed models used for our analyses are robust to missing data, allowing inclusion of all available observations in the models.

Measures of cognition and neglect were only assessed at admission; therefore, only baseline values were included in the models (Table 4-5). Consequently, the results related to these covariates should be interpreted with caution, as they reflect only baseline associations and may not capture the influence of evolving cognitive or attentional deficits on longitudinal outcomes.

An additional limitation is that rehabilitation was not standardized across participants, as therapy interventions were individualized based on clinical needs. Therefore, the observed trajectories likely reflect a combination of spontaneous recovery and therapy effects. While this heterogeneity may have introduced variability and confounded the interpretation of recovery patterns across domains, it also enhances the ecological validity of the findings by reflecting real-world clinical practice.

Finally, we lacked standardized measures to characterize stroke severity and UE motor impairment in our cohort, such as the Fugl-Meyer or the NIHSS, as recommended by the Stroke Recovery and Rehabilitation Roundtable (67). This limits comparability with other studies and the contextualization of our sample in terms of impairment severity.

Conclusion

Recovery of UE sensorimotor capacity in the subacute phase post-stroke is characterized by substantial inter-individual variability and partially distinct trajectories across domains. Bilateral capacity and proprioception emerged as distinct and functionally meaningful construct, contributing uniquely to ADL performance beyond unilateral motor capacity alone, indicating that reliance on unimanual assessments may overlook functionally relevant deficits. Together, these findings support the use of comprehensive assessment strategies integrating unilateral, bilateral, and somatosensory measures to better capture real-world function. Such an approach may facilitate the development of individualized rehabilitation strategies tailored to specific impairment and recovery profiles.

Abbreviations

ADLs
Activity of Daily Living
APM
Arm Position Matching task
BoB
Ball on Bar task
CAHAI
Chedoke Arm and Hand Activity Inventory

LMM
Linear Mixed Model
MoCA
Montreal Cognitive Assessment
PHQ-9
Patient Health Questionnaire
UE
Upper-Extremity
VGR
Visually Guided Reaching task.

Declarations

Ethics approval and consent to participate

All participants provided written informed consent prior to enrolment in the study.This study was approved by the Ethics Committee of the Centre Intégré Universitaire de Santé et de Services Sociaux de la Capitale Nationale (Ethics Certificate Number #2022-2550) on April 12, 2022.

Consent for publication

Not applicable

Availability of data and materials

Data available upon request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

LGP was involved in the conception and design of the study, data acquisition and analysis, interpretation of findings, and writing the manuscript. MR and CM were involved in the conception and design of the study, data interpretation, and manuscript revision. All authors read and approved the final manuscript.

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Figures

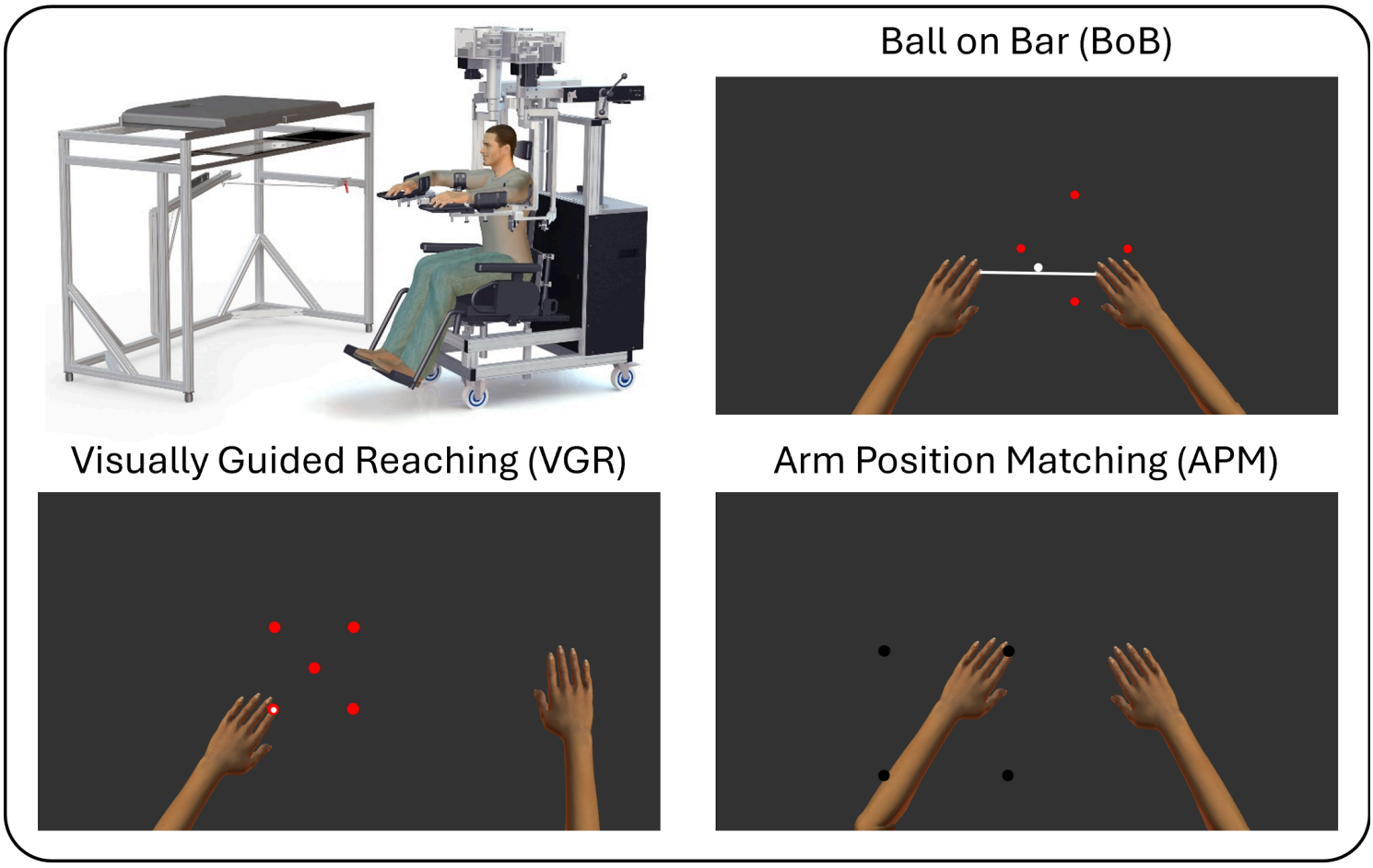


Figure 1

Experimental setup for the Kinarm Exoskeleton Lab and representation of the four robotic tasks. Top-left panel is reproduced with permission from Kinarm (https://kinarm.com/).

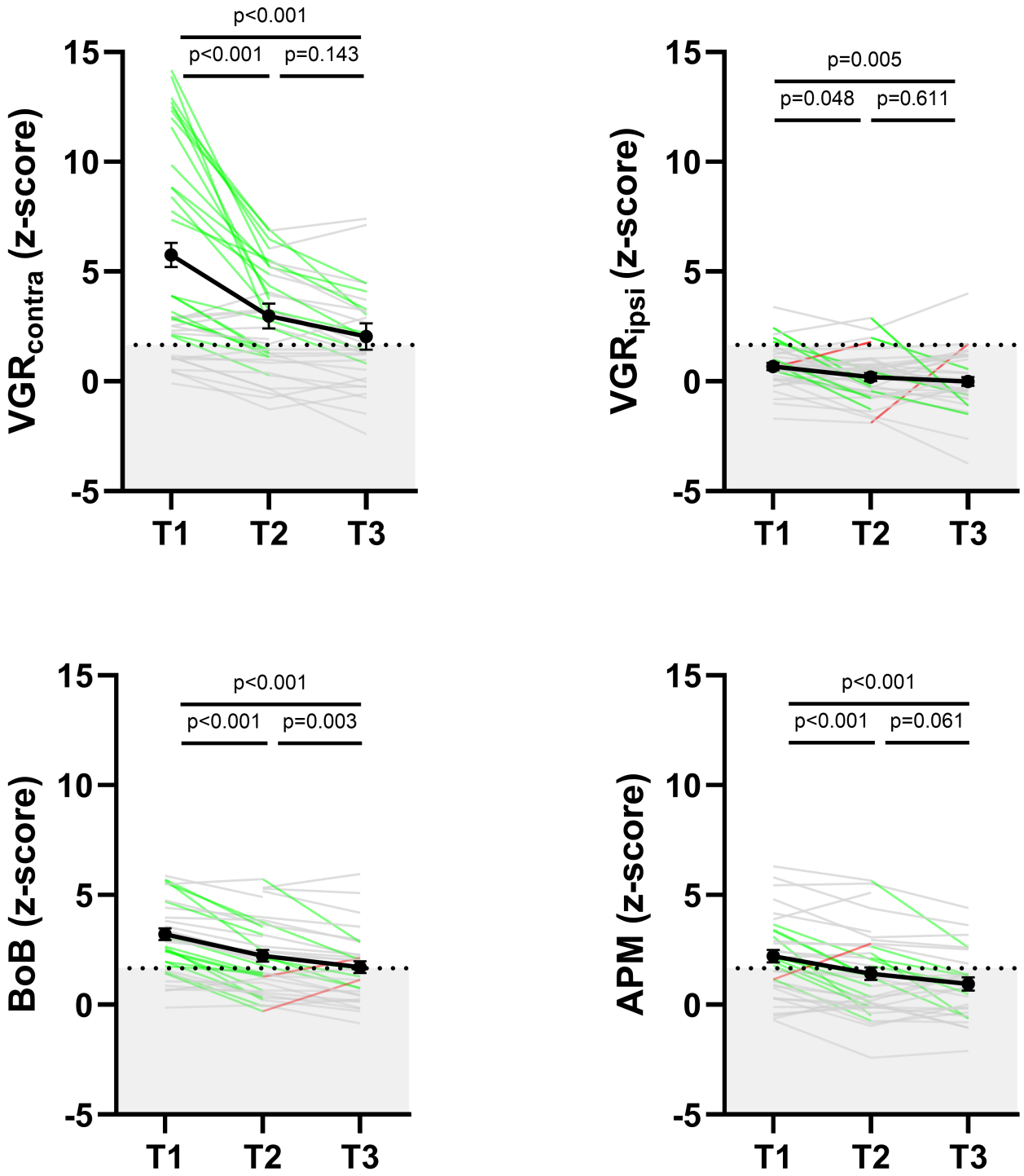


Figure 2

Change in performance in robotic tasks and clinical assessment during the subacute phase post-stroke. Bold lines and circles represent the estimated marginal means and standard errors derived from the linear mixed models. Grey lines represent individual trajectories of participants. Green and red lines represent participants who showed a significant improvement (green) or deterioration (red) in performance between two time points. The dashed horizontal line represents the impairment threshold of (z-score < 1.65).

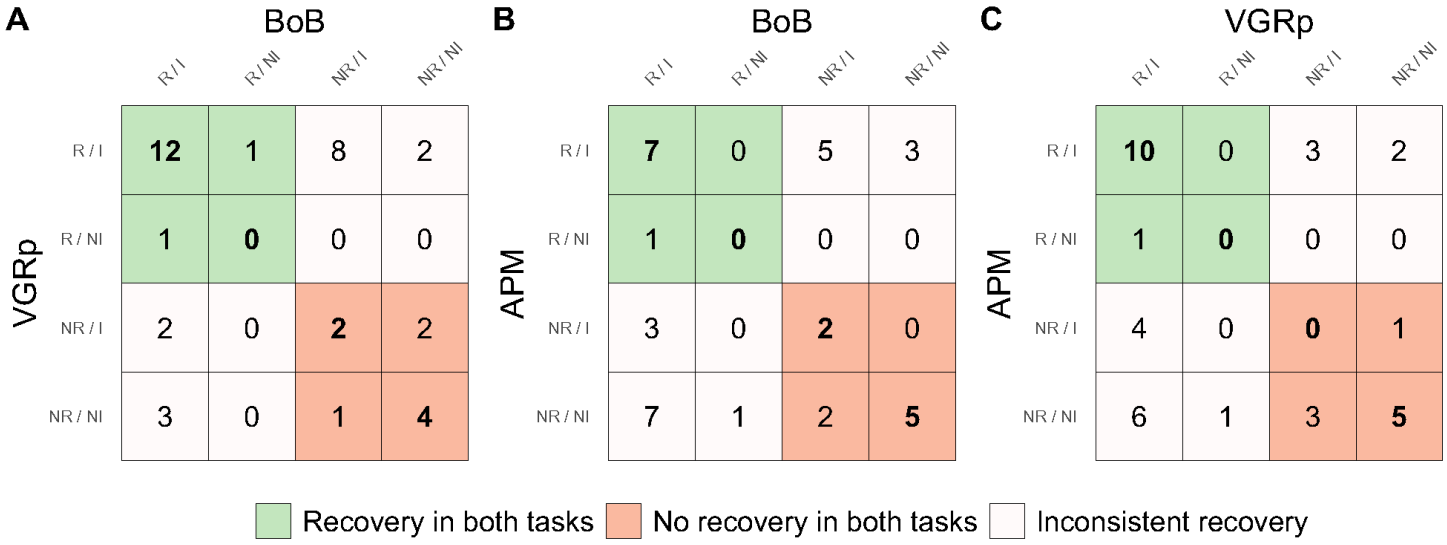


Figure 3

Matrices comparing individual recovery trajectories across domains: unilateral vs bilateral (**A**), unilateral vs proprioceptive (**B**), and bilateral vs proprioceptive (**C**). Classification was based on impairment at T1 (I, Impaired; NI, Not Impaired) and recovery between T1–T3 (R, Recovery; NR, No Recovery). **Bold**numbers (top-left to bottom-right diagonal) represent participants with both consistent impairment status at T1 and concordant recovery trajectories across tasks.