

# Feedback and Cognition in Arm Motor Skill Reacquisition After Stroke

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**Background and Purpose**—A debated subject in stroke rehabilitation relates to the best type of training approach for motor recovery. First, we analyzed the effects of repetitive movement practice in 2 feedback conditions (knowledge of results [KR]; knowledge of performance, [KP]) on reacquisition of reaching. Second, we evaluated the impact of cognitive impairment on motor relearning ability.

**Methods**—A randomized controlled clinical trial was conducted in Montreal-area rehabilitation centers between 1998 and 2003 with 37 patients with chronic hemiparesis. Patients were randomly assigned to 3 groups: (1) KR (n=14) practiced a reaching task involving 75 repetitions per day, 5 days per week for 2 weeks, with 20% KR about movement precision; (2) KP (n=14) trained on the same task and schedule as KR but with faded KP about joint motions; and (3) control (C; n=9) practiced a nonreaching task. Physical (motor impairment, function) and kinematic (movement time, precision, segmentation, variability) variables were assessed before and after (immediately, 1 month) practice. Cognitive functions (memory, attention, mental flexibility, planning) were also evaluated.

**Results**—Kinematic gains in KR (precision) and KP (time, variability) exceeded those in C and depended on memory and mental flexibility deficits. In KP, more severely impaired patients made the most clinical gains ( $>2\times C$ ), which were related to memory and planning abilities.

**Conclusions**—Use of KP during repetitive movement practice resulted in better motor outcomes. Stroke severity together with cognitive impairments are important factors for choosing motor rehabilitation interventions after stroke. (*Stroke*. 2006;37:1237-1242.)

**Key Words:** randomized controlled trials ■ rehabilitation ■ stroke ■ cognition

Rehabilitation of arm motor function after stroke is a challenge to rehabilitation professionals. Of stroke victims, 30% to 66% continue to experience arm motor dysfunctions for  $>6$  months.<sup>1</sup> Various rehabilitation approaches have been used to improve skill reacquisition of the impaired arm. According to a review of 300 randomized controlled trials (RCTs) incorporating 2686 patients, enhanced clinical outcomes depend on 2 key elements: training intensity and task specificity.<sup>2</sup> Most of these studies used various outcomes at different levels of body structure, activity, and participation measured at different times after stroke onset, making conclusions about intervention outcomes difficult.

Basic neurophysiological research suggests that repetitive motor activity forms the basis of skill (re)acquisition. Aside from practice, the type of feedback provided to the performer is another key factor in motor skill reacquisition. Feedback variables include the nature (knowledge of results [KR] or knowledge of performance [KP]), timing (concurrent, terminal), and frequency (summary, faded, etc) of information

delivery to the learner.<sup>3</sup> KR or terminal feedback about goal-related movement outcomes has been the focus of much research in healthy<sup>4,5</sup> as well as stroke<sup>6,7</sup> subjects, mostly because of the ease with which it can be manipulated and quantified. In contrast, concurrent feedback about goal-related performance (KP) is used frequently in stroke rehabilitation. Determining which feedback type optimizes motor recovery would increase the success of rehabilitation interventions.

We hypothesized that in patients with chronic hemiparesis, the kinematic and clinical effects of repetitive movement practice would differ according to the type of feedback provided. One participant group received 20% terminal KR about movement precision, and the other received faded concurrent KP about specific movement impairments (decreased active joint motion). Because cognitive functioning may potentially modify training effects,<sup>8</sup> we also hypothesized that motor improvements would be related to cognitive abilities. See the abstract of Cirstea et al for preliminary results.<sup>9</sup>

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**TABLE 1. Demographics, Stroke History, Motor Task Parameters, and Clinical Evaluations in Stroke Patients**

Characteristics	KR (n=14)	KP (n=14)	C (n=9)
Gender			
Male	10	7	6
Female	4	7	3
Age* (y)	55.7 (15.4)	59.1 (17.9)	64.5 (14.1)
Time since onset* (mo)	12.1 (4.9)	11.4 (6.3)	11.1 (5.9)
Lesion location			
Cortical	6	5	2
Subcortical	3	5	4
Cortical+subcortical	5	4	3
MT1*			
Height (cm)	83.7 (4.9)	81.1 (2.2)	81.3 (2.0)
Distance (cm)	76.7 (11.5)	71.6 (11.7)	70.2 (7.6)
Physical*			
FM	45.8 (14.1)	40.8 (21.8)	47.7 (13.0)
CSI	6.5 (1.7)	7.7 (2.6)	7.7 (2.4)
TEMPA	-7.7 (6.3)	-7.3 (5.6)	-7.1 (5.0)
Cognitive†			
Verbal memory	34.7 (9.05)	29.1 (10.4)	26.7 (8.2)
Visuospatial memory	17.7 (14.4)	32.1 (21.8)	23.6 (10.3)
Attention	64.4 (23.9)	62.6 (8.7)	58.6 (17.9)
Mental flexibility	54.6 (11.7)	51.3 (7.1)	59.6 (9.9)
Planning	58.1 (33.5)	53.7 (29.5)	35.4 (20.9)

\*Mean (SD); †mean (SD) of Z score (%).

## Methods

### Participants

Candidates selected from discharge lists of Montreal-area rehabilitation centers between 1998 and 2003 were no longer receiving inpatient or outpatient treatment. Out of a 600-candidate pool, 60 met inclusion criteria according to chart review (Figure 1): (1) single stroke in the dominant hemisphere 3 to 24 months previously, and (2) able to reach with the impaired arm (at least stage 2 on

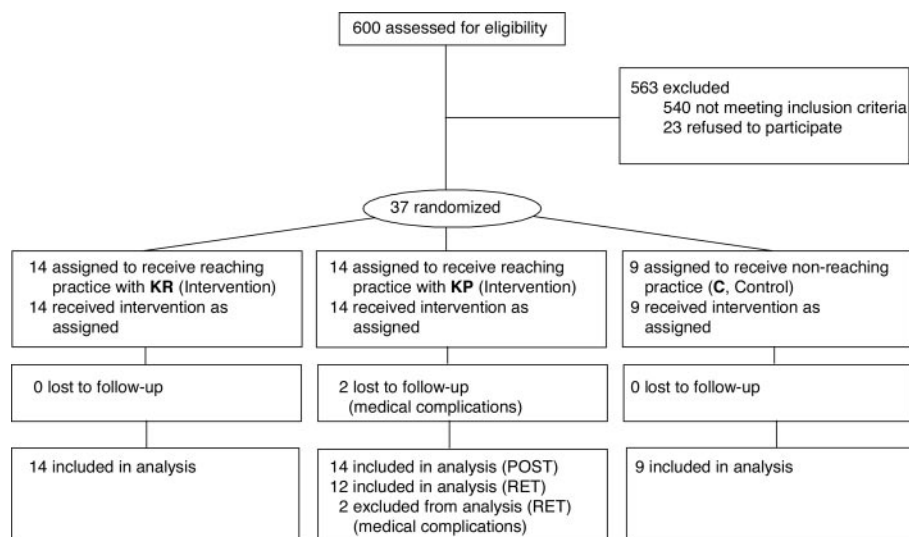
Chedoke-McMaster Stroke Assessment<sup>10</sup>). Individuals were excluded if they had occipital, cerebellar, or brain stem lesions, multiple strokes, major perceptual deficits, apraxia, shoulder subluxation, pain, or other neurological disorders. Of 60 candidates contacted, 37 expressed willingness to participate. After signing informed consent forms approved by local ethics committees, all but 2 participants completed the protocol. These 2 patients did not complete the follow-up (Retention [RET]) because of medical complications. No gender or racial/ethnic-based differences were present between groups. There were 14 subjects in each intervention group and 9 in the control (C) group. Despite the difference in number of participants between groups, demographic data were similar (Table 1). Ten healthy subjects (43.3±18.2 years; 6 females and 4 males) were recruited for comparison data.

### Design

In this double-blind RCT, patients were stratified by age (±5 years) and severity (±1 CM) and randomly assigned to intervention (KR, KP) or C groups in blocks of 6 by an assistant who did not participate in subject evaluation or treatment. Physical, neuropsychological, and kinematic assessments were done before (PRE) a 10-day intervention. Physical and kinematic evaluations were repeated immediately (POST) and 1-month after (RET) intervention. Evaluators were unaware of patient group assignment. Participants were instructed to avoid mentioning details about their study experience to evaluators. Although therapists were aware that different patients received different training approaches, all involved were uninformed of study hypotheses or outcome measures.

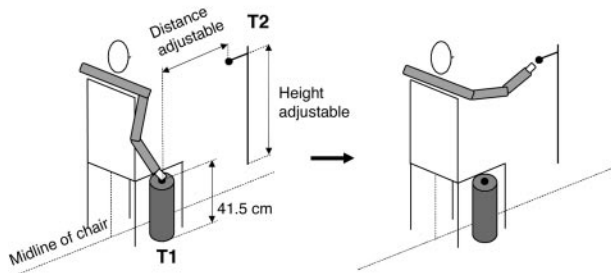
The intervention, supervised by experienced physical therapists, consisted of movement repetition (1 hour per day) for 10 sessions delivered over 2 weeks. The training goal for all groups was to make movements as quickly and precisely as possible. The number of repetitions per session (n=75) was considered to be "intensive" practice according to previous results indicating that the learning curve asymptote in severely impaired patients occurred after 36±14 trials.<sup>7</sup> Intervention groups (KR, KP) practiced a pointing movement (motor task 1 [MT1]; Figure 2) without vision so that movement repetition relied on proprioceptive information considered crucial for motor recovery after stroke.<sup>11</sup>

Groups received different verbal feedback: (1) KR: terminal information about movement precision; at movement end, participants opened their eyes and corrected their finger position closer to the final target; and (2) KP: concurrent information about joint motion (shoulder flexion, elbow extension) during movement. To minimize dependence on feedback, summary length of KR was 5 trials (20%), whereas KP was given on a faded schedule (first 25



**Figure 1.** Flow of stroke participants through RCT stages.

## Motor Task 1



**Figure 2.** Experimental design. Initial target (T1)=circle located on the cylinder; final target (T2)=circle located in front of the subject.

trials: every trial; second 25 trials: every second trial; last 25 trials: every fifth trial). The C group followed the same protocol in terms of repetition intensity, but they practiced finger/hand tapping. This group was included to control for changes attributable to spontaneous recovery and extra attention received by the intervention groups.

## Evaluations

### Physical

Valid and reliable tests were used to assess arm motor impairment (arm section of Fugl-Meyer Scale [FM]<sup>12</sup>), elbow spasticity (Composite Spasticity Index [CSI]<sup>13</sup>), and arm function (Upper Extremity Performance Test for the Elderly [TEMPA]<sup>14</sup>). The FM evaluates muscle tone, range of motion, tendon reflexes, and proximal/distal voluntary arm movements, with a normal score of 66, in addition to proprioception on an 8-point scale. The CSI assesses biceps tendon jerks, resistance to passive stretch, and wrist clonus for scores ranging from 4 (normal tone) to 16 (severe spasticity). TEMPA incorporates unimanual and bimanual daily life tasks in 2 functional scores ranging from 0 (normal) to -12 (unimanual) and -15 (bimanual).

### Neuropsychological

Performance across 5 cognitive domains was often impaired after stroke was assessed:<sup>15</sup> (1) verbal memory (Wechsler Memory Scale Stories [WMSS]; Rey Auditory Verbal Learning Test [RAVLT]); (2) visuospatial memory (Rey-Osterrieth Complex Figure Test [ROCFT]); (3) attention (Cancellation test [CT]; ROCFT); (4) mental flexibility (Wisconsin Card Sorting Test [WCST]; Stroop Test [ST]); and (5) planning/problem-solving abilities (Tower of London [TOL]). For each test, a Z score (%) was calculated by selecting a representative variable from each test: WMSS (immediate, 90-minute delayed recall), RAVLT (5 trials, 30-minute delayed recall of 15-word list), ROCFT (copy, 40-minute delayed recall), CT (number of omission errors), WCST (number of categories), ST (interference score), and TOL (number of total moves). Mean Z scores were determined for each cognitive domain from Z scores of individual tests and compared with normative data.

### Magnetic Resonance Imaging

MRI examinations (General Electric Sigma 1.5-T MRI) were made on 5-mm slices using a 256 matrix. T1-weighted images (repetition time [TR]=500 ms; echo time [TE]=20 ms) and proton density-, and T2-weighted images (TR=2595 ms; TE=20/80 ms) were obtained in the axial plane. Axial T2-weighted images were obtained with a fluid-attenuated inversion recovery sequence (TR=5000 ms; TE=150 ms; inversion time=1900 ms). Infarcts were detected using proton density and T2, and hemorrhage using T1 images. For 10 patients in whom MRI scanning was contraindicated, lesion location was obtained by chart review. Lesions were classified according to area of involvement as cortical, subcortical, or cortical+subcortical (Table 1).

### Kinematic

Seated participants performed 25 pointing movements (MT1) with the dominant (impaired) arm from an initial target located ipsilater-

ally on a 41.5-cm high platform, lateral to the right hip, to a sagittally located final target (target 2) in the contralateral workspace (Figure 2). Target 2 was adjusted to shoulder height and placed just beyond arm's reach so that no tactile feedback was provided. Target heights and distances were consistent between groups (Table 1). This task was chosen because it combined motor elements identified previously as being altered after stroke in a natural movement.<sup>7,16</sup> Subjects were instructed to "point to target 2 as precisely and as quickly as possible in a single uncorrected movement and to maintain the final arm position until hearing a tone." Subjects practiced MT1 5 times and then 25 repetitions were recorded. Learning generalization was assessed with a transfer task (motor task 2 [MT2]) consisting of 25 pointing movements to target 2 located in the ipsilateral workspace.

Kinematic data were recorded with a 3D optical tracking system (Optotrak 3010; Northern Digital) using infrared-emitting diodes placed on the index finger, ulnar head, lateral epicondyle, acromion processes, and midsternum. Movements were recorded for 2 to 4 seconds at 100 Hz and digitally low-pass filtered at 20 Hz (second-order Butterworth filter). To avoid fatigue, 10-second rest periods were allowed between trials and 2 minutes on request.

### Data Analysis

Five kinematic outcomes were analyzed: movement time, precision, segmentation and variability of velocity and precision. Values were determined from individual trials, and means and SDs were calculated by participant and session.

Tangential velocity was computed from the velocity vector magnitude, obtained by 3-point numerical differentiation of  $x$ ,  $y$ ,  $z$  positions of the finger marker. Movement onsets and offsets were defined as the times at which velocity surpassed/fell and remained above/10% of the maximal peak velocity to avoid variability attributable to baseline oscillations caused by tremor or instability. Precision was evaluated as absolute error (root mean-squared distance) between final finger and target 2 positions, and segmentation was the number of peaks (velocity increases followed by velocity decreases) in the finger velocity profile.

Consistency of peak velocity ( $v$ ) and precision ( $p$ ) were evaluated by coefficients of variability (CV $v$ , CV $p$ : SD/mean).

### Sample Size

The number of participants was determined according to Cohen<sup>17</sup> and preliminary results.<sup>9</sup> Power analysis relied on specifications of movement time: SE=0.28 seconds, indices of improvement [II]=-0.25 for KP (see below); -0.16 for KR and -0.05 for C. For KP, PRE-POST correlation of movement time measurements was 0.98, and the power to detect a significant interaction was 81%. According to this analysis, 14 participants per group were required.

### Statistical Analysis

Baseline data from healthy and stroke participants were compared using  $t$  tests for independent samples or Mann-Whitney  $U$  tests for continuous variables. For hypothesis 1, the effects of repetitive practice with different feedback types on behavioral outcomes were determined with between-group comparisons using group $\times$ time mixed-model ANOVAs having 3 levels per factor and least significant difference post hoc tests. Effect sizes for differences were measured using coefficient of responsiveness (CR)  $\{CR=[\text{mean (PRE-POST)}_{\text{intervention}} - \text{mean (PRE-POST)}_{\text{control}}]/\text{SDPRE}_{\text{pooled}}\}$ . Pearson correlations analyzed relationships between: (1) baseline physical and cognitive scores, and (2) changes in behavioral outcomes using II  $\{II=[\text{PRE-POST}]/\text{PRE}\}$  and indices of retention  $\{[\text{POST-RET}]/\text{POST}\}$ . For hypothesis 2, multiple regression analyses assessed relationships between baseline cognitive and behavioral indices (Statview; SAS Institute; v5.0). Significance levels of  $P<0.05$  were used.

## Results

### Group Level

#### PRE Intervention

Patients with hemiparesis made slower, less precise, more segmented, and more variable movements compared with

**TABLE 2. Preintervention: Kinematic Outcomes (mean [SD]) in Healthy and Stroke Participants**

Kinematic Outcomes	Healthy	Stroke
Time (s)	0.7 (0.1)	1.3 (0.3)**
Precision (cm)	6.5 (1.0)	10.3 (5.5)**
Segmentation (No. peaks)	1.2 (0.6)	3.6 (2.4)*
CV velocity (%)	11.9 (3.7)	16.5 (5.3)**
CV precision (%)	28.4 (12.2)	31.6 (13.2)

\* $P < 0.05$ ; \*\* $P < 0.01$ .

age- and gender-matched healthy subjects (Table 2). There were no initial differences in mean age, chronicity, and clinical scores between stroke groups (Table 1). For kinematic outcomes, all groups were comparable except that movements in KR were less variable than those in KP or C with respect to velocity ( $P < 0.01$ ; Figure 3).

**Intervention and RET**

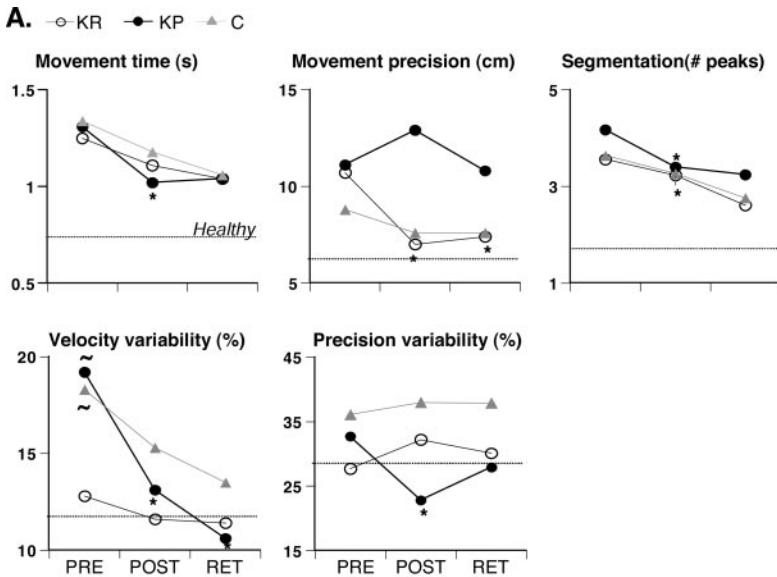
All groups improved movement time by an average of 229 ms at POST and 299 ms at RET ( $F_{2,66} = 14.63$ ;  $P < 0.0001$ ), segmentation by 0.5 peaks at both POST and RET ( $F_{2,66} = 21.99$ ;  $P < 0.0001$ ), and velocity variability by 4% at POST and 5% at RET ( $F_{2,66} = 18.34$ ;  $P < 0.0001$ ; Figure 3A). In KP, improvements in movement time ( $F_{1,27} = 4.39$ ) and segmentation

( $F_{1,27} = 4.35$ ;  $P < 0.05$ ) were transferred to MT2. Arm motor impairment (FM;  $F_{1,34} = 12.24$ ;  $P < 0.002$ ) and unilateral function (TEMPA;  $F_{1,27} = 5.57$ ;  $P < 0.03$ ) but not spasticity improved in all groups with no between-group differences.

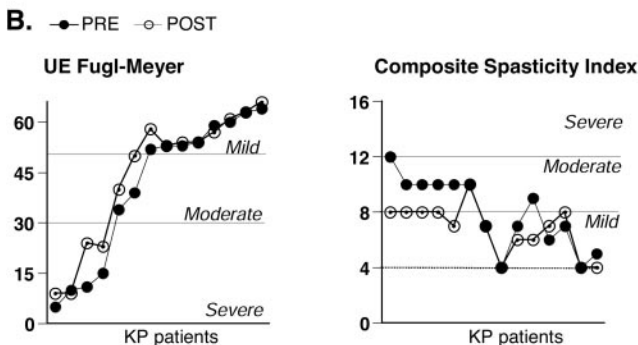
Between groups, improvements in precision in KR (CR=45.3%) and in movement time (CR=57.4%) and variability (CR<sub>v</sub>=86.8%; CR<sub>p</sub>=91.1%) in KP were larger than C ( $P < 0.01$ ). Kinematic changes were accompanied by a decrease in spasticity (CR=47.1%) in KP compared with C ( $P < 0.05$ ).

By group, movements were more precise ( $F_{2,66} = 2.77$ ;  $P < 0.001$ ) in KR, faster ( $F_{2,66} = 7.57$ ;  $P < 0.001$ ), less segmented ( $F_{2,66} = 6.06$ ;  $P < 0.01$ ), and more consistent (CV<sub>v</sub>:  $F_{2,66} = 19.5$ ; CV<sub>p</sub>:  $F_{2,66} = 4.09$ ;  $P < 0.05$ ) in KP and less segmented ( $F_{2,66} = 20.9$ ;  $P < 0.001$ ) and more consistent (CV<sub>v</sub>:  $F_{2,66} = 5.16$ ;  $P < 0.01$ ) in C. The increase in precision in KR was correlated with an increase in movement speed (Ierror versus Iitime;  $r = 0.63$ ). KP and C also made faster movements that were, however, not correlated with increased precision.

Retention of improved kinematics was related to baseline FM scores. For KR: retention of increased precision ( $r = 0.70$ ); for KP: retention of decreased movement time ( $r = 0.44$ ) and segmentation ( $r = 0.43$ ), increased precision variability ( $r =$



**Figure 3. A,** Kinematic outcomes (mean) for KR, KP, and C in all sessions. Asterisks indicate differences between sessions; ~, baseline differences ( $P < 0.05$ ). Horizontal lines indicate healthy values. B, KP: FM and CSI values in PRE and POST. Horizontal lines divide in severe, moderate, and mild impairment.



0.53), and its retention ( $r=0.58$ ); for C: retention of decreased segmentation ( $r=0.59$ ).

### Behavioral Outcomes and Cognitive Scores

Cognitive scores in stroke patients, on average, were decreased compared with the normative group (Table 1) and for all but planning were correlated with baseline arm clinical scores: FM (verbal memory:  $r=0.41$ ; visuospatial memory:  $r=0.39$ ; attention:  $r=0.52$ ; mental flexibility:  $r=0.39$ ); CSI (visuospatial memory:  $r=-0.30$ , attention:  $r=-0.39$ ; flexibility:  $r=-0.43$ ); and TEMPA (verbal memory:  $r=0.38$ ; attention:  $r=0.43$ ).

In KR, there was no correlation between increased precision and cognitive scores. In KP, better retention of decreased segmentation ( $r^2=0.95$ ) and decreased precision variability ( $r^2=0.94$ ) was related to better verbal memory ( $\beta=1.52$ ) and fewer deficits in mental flexibility ( $\beta=-1.46$ ) and planning ability ( $\beta=-0.65$ ), respectively ( $P<0.05$ ). Interestingly, in KP, larger clinical improvements (FM,  $r^2=0.96$ ; TEMPA,  $r^2=0.84$ ;  $P<0.05$ ) were related to fewer deficits in memory abilities (FM: verbal,  $\beta=-0.86$ ; visuospatial,  $\beta=-1.58$ ) and better planning ability (FM:  $\beta=0.71$ ; TEMPA:  $\beta=-0.88$ ). In C, better retention of decreased velocity variability ( $r^2=0.83$ ;  $P<0.05$ ) was related to fewer deficits in mental flexibility ( $\beta=-0.88$ ). No correlations between clinical improvements and cognitive scores were identified in KR and C.

### Subject Level

Only the most impaired patients in KP improved with intervention according to FM (5 of 6 patients) and CSI (6 of 7), respectively (Figure 3B). The FM improvement was correlated with improvement in precision variability ( $r=0.73$ ;  $P<0.05$ ).

### Discussion

As shown previously,<sup>19,20</sup> our results demonstrate that given appropriate intervention, patients with chronic hemiparesis preserve the ability to improve motor skills. Our intervention emphasized systematic repetition of joint movements (elbow flexion/extension, shoulder flexion/horizontal adduction) that are particularly disrupted after stroke<sup>16,21</sup> and relevant for successful accomplishment of many daily life tasks. Interestingly, motor improvements depended on the type of feedback provided in training. Compared with C, participants who received feedback about movement outcome (precision) improved only that outcome, whereas those who had feedback about movement performance (joint movement) improved 4 of 5 movement outcomes (Figure 3). All improvements persisted 1 month after intervention. Because similar gains in retention occurred in both intervention groups, it is unlikely that performance differences were attributable to differences in feedback presentation (20% summary KR versus 26.6% average faded KP). However, differences may be attributed to different motor control processes associated with different types of feedback.<sup>22</sup> Although the behavioral goal was to make more precise and faster movements, the group receiving augmented information about precision (KR) made more precise and faster movements, although overall, their gains in speed were less than the other groups. In contrast, given the

same behavioral goal, the group receiving movement pattern information (KP) improved movement time and variability at the expense of precision (Figure 3A). These results reflect differences in performance strategies based on feedback type. Because the intervention consisted of repetition of a simple pointing task instead of more functional training, we did not expect functional upper limb changes. Functional recovery could be evaluated in a study combining functional training with specific feedback about motor patterns.

Patients with initially severe arm paresis reportedly have a lower probability of functional recovery compared with those with mild arm paresis.<sup>23</sup> Our results showed that given appropriate feedback (ie, KP), even severely impaired patients decreased motor impairment (83% to 86% of patients), and 75% improved motor function.

Platz and Denzler<sup>24</sup> suggested that cognitive processes only minimally determine the potential for motor recovery after stroke. Our results are in contrast to this viewpoint and suggest that successful motor intervention may involve varying degrees of cognitive processing depending on the cognitive demands of the intervention. For example, in KR, there was no correlation between improvements in precision and cognitive scores. This may be explained by the fact that feedback about precision does not tap into intellectual or executive functioning processes. In contrast, in KP, motor and clinical improvements were related to better memory, mental flexibility, and planning abilities. Presumably, these cognitive processes are more involved in making use of critical information about moving and adapting motor behavior to improve efficiency. The discrepancy between our results and those of Platz and Denzler may lie in differences in the severity of paresis. They studied patients with mild motor and cognitive impairments who may have already reached maximal clinical scores, whereas in our study, participants had more severe motor and cognitive impairments. In addition, because all groups in our study had similar baseline cognitive scores, differences in skill reacquisition seem to be related to the singular cognitive demands required by the feedback types and not to initial between-group differences.

Compared with the intervention groups, group C also improved, albeit less so, in 2 kinematic outcomes. These benefits may be attributed to the amount of additional time spent in therapy that has been suggested to be a factor leading to better outcomes independently of the type of intervention applied.<sup>25</sup>

Finally, the motor improvements in the KP group transferred to a related task as opposed to task-specific training approaches.<sup>26</sup> This may be explained by the learning of a generalized set of movement combinations as a basis for an entire class of actions.<sup>3</sup> Included in this process is the opportunity for learners to perform error detection and self-correction, which may be facilitated by the use of decreased feedback frequency. Consequently, our results suggest that learning was enhanced by providing feedback with a faded frequency.

The present study incorporated critical factors related to motor relearning after stroke, such as type, timing and frequency of feedback, and initial motor and cognitive impairment levels. The relatively small sample size limits generalization of results. However, our findings may have

important implications for motor rehabilitation after stroke. First, training incorporating information and practice of specific motor elements may have a larger impact on motor recovery. Second, the assessment and modification of cognitive impairment are essential elements of motor rehabilitation programs.

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### References

- Richards L, Pohl P. Therapeutic interventions to improve upper extremity recovery and function. *Clin Geriatr Med*. 1999;15:819–832.
- Foley NC, Teasell RW, Bhogal SK, Speechley MR. Stroke rehabilitation evidence-based review: methodology. *Top Stroke Rehabil*. 2003;10:1–7.
- Schmidt R. *Motor and Learning: A Behavioral Emphasis*. Champaign, Ill: Human Kinetics; 1988.
- Winstein CJ. Knowledge of results and motor learning-implications for physical therapy. *Phys Ther*. 1991;71:140–149.
- Winstein CJ, Schmidt R. Sensorimotor feedback. In: Holding D, ed. *Human Skills*. Chichester, England: John Wiley & Sons; 1989:17–47.
- Butefisch C, Hummelsheim H, Denzler P, Mauritz KH. Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand. *J Neurol Sci*. 1995;130:59–68.
- Cirstea MC, Ptito A, Levin MF. Arm reaching improvements with short-term practice depend on the severity of the motor deficit in stroke. *Exp Brain Res*. 2003;152:476–488.
- Mercier L, Audet T, Hebert R, Rochette A, Dubois MF. Impact of motor, cognitive, and perceptual disorders on ability to perform activities of daily living after stroke. *Stroke*. 2001;32:2602–2608.
- Cirstea MC, Ptito A, Forget R, Levin MF. Arm motor improvements in stroke patients may depend on the type of training. *Soc Neurosci Abstract*. <http://abstracts.sfn.org/>, 2000.
- Gowland C, Stratford P, Ward M, Torresin W, Van Hullenar S, Sanford J, Barreca S, Vanspall B, Plews N. Measuring physical impairment and disability with the Chedoke-McMaster Stroke Assessment. *Stroke*. 1993;24:58–63.
- Woldag H, Hummelsheim H. Evidence-based physiotherapeutic concepts for improving arm and hand function in stroke patients: a review. *J Neurol*. 2002;249:518–528.
- Berglund K, Fugl-Meyer AR. Upper extremity function in hemiplegia. A cross validation study of two assessment methods. *Scand J Rehabil Med*. 1986;18:155–157.
- Levin MF, Hui-Chan CW. Relief of hemiparetic spasticity by TENS is associated with improvement in reflex and voluntary motor functions. *Electroencephalogr Clin Neurophysiol*. 1992;85:131–142.
- Desrosiers J, Hebert R, Dutil E, Bravo G, Mercier L. Validity of a measurement instrument for upper extremity performance: the TEMPA. *Occup Ther J Res*. 1994;14:267–281.
- Lezak M. *Neuropsychological Assessment*. 3rd ed. New York, NY: Oxford University Press; 1995.
- Cirstea MC, Levin MF. Compensatory strategies for reaching in stroke. *Brain*. 2000;123:940–953.
- Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Hillsdale, NJ: Erlbaum; 1988.
- Guyatt GH, King DR, Feeny DH, Stubbings D, Goldstein RS. Generic and specific measurement of health-related quality of life in a clinical trial of respiratory rehabilitation. *J Clin Epidemiol*. 1999;52:187–192.
- Platz T, Denzler P, Kaden B, Mauritz KH. Motor learning after recovery from hemiparesis. *Neuropsychologia*. 1994;32:1209–1223.
- Kwakkel G, Wagenaar RC. Effect of duration of upper- and lower-extremity rehabilitation sessions and walking speed on recovery of interlimb coordination in hemiplegic gait. *Phys Ther*. 2002;82:432–448.
- Lum PS, Burgar CG, Shor PC. Evidence for strength imbalances as a significant contributor to abnormal synergies in hemiparetic subjects. *Muscle Nerve*. 2003;27:211–221.
- McNevin NH, Shea CH, Wulf G. Increasing the distance of an external focus of attention enhances learning. *Psychol Res*. 2003;67:22–29.
- Nakayama H, Jorgensen HS, Raaschou HO, Olsen TS. Recovery of upper extremity function in stroke patients: the Copenhagen Stroke Study. *Arch Phys Med Rehabil*. 1994;75:394–398.
- Platz T, Denzler P. Do psychological variables modify motor recovery among patients with mild arm paresis after stroke or traumatic brain injury who receive the arm ability training? *Restor Neurol Neurosci*. 2002;20:37–49.
- Aichner F, Adelwöhrer C, Haring HP. Rehabilitation approaches to stroke. *J Neural Transm Suppl*. 2002;63:59–73.
- Kwakkel G, Kollen B, Wagenaar RC. Therapy impact on functional recovery in stroke rehabilitation: a critical review of the literature. *Phys Ther*. 1999;85:377–391.

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