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Kinematic Assessment of Manual Skill Following Functional Hand Surgery in Tetraplegia

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To determine whether surgical key grip reinforcement actually leads to a better movement ability we developed a procedure for the kinematic analysis of manual skill following hand surgery in tetraplegia. The functional results of surgery in 5 cases were examined by the kinematic analysis of drawing movements using an electronic pen and a digitizer under 3 conditions: with eyes open, with eyes closed, and while performing a concurrent arithmetic task. Movement velocity and dysfluency (ie, the number of velocity changes per centimeter) were measured before and at several moments after surgery during subsequent rehabilitation. Both movement velocity and dysfluency showed good stability across repeated trials and were consistently affected by visual deprivation. Movement velocity showed a 39% increment between the first and last assessment. Although grip strength increased in all patients, it was not associated with the change of movement velocity. These results suggest that other factors (eg, deep sensibility, cognition, muscle coordination) play a critical role in the ability to use improved grip force for controlling drawing movements and emphasize the value of a kinematic assessment besides measuring isolated grip force in the evaluation of functional hand surgery. (*J Hand Surg* 2000;25A:1140–1146. Copyright © 2000 by the American Society for Surgery of the Hand.)

Key words: Kinematic assessment, manual skill, hand surgery, rehabilitation, tetraplegia.

Improvement of hand function is considered of great importance in the rehabilitation of tetraplegic patients. In the past decades, reconstructive hand surgery has received increasing interest.^{1–4} Until

now the results of functional hand surgery have been evaluated by measuring grip force^{5–9} or by using qualitative or semiquantitative clinical dexterity tests and questionnaires.^{10–17} No accepted kinematic procedure exists, however, for the analysis of hand movements in tetraplegic patients, which is directed at the level of manual skill instead of isolated hand functions.^{18,19} Thus, the goal of this study was to develop a procedure to kinematically assess line drawing skill following reconstructive hand surgery in tetraplegia.

Line drawing was assessed before and after surgical key grip reinforcement using a computerized system that was originally developed for the kinematic analysis of hand writing in healthy subjects.²⁰ The line drawing task had to be performed under

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different conditions to test the robustness of motor performance. Full attention and vision were available in a basic task condition. In a second condition the level of automaticity of line drawing was assessed by adding a concurrent arithmetic task. In a third condition the degree of visual dependency was assessed by visual deprivation. These 2 task manipulations were added to the basic condition because a temporary increase in the attentional or visual control of line drawing, resulting from the need for the central nervous system to adapt to the altered anatomy of the treated forearm and hand, might be expected shortly after functional hand surgery.²¹ For instance, it has been shown in many clinical experiments that the degree of attentional or visual dependency of motor control may be temporarily enhanced after acute structural changes to the neuromuscular system.²²⁻²⁴

Line drawing was assessed before surgery and several times after surgery because improved performance might become visible only after a certain training period. Moreover, at all assessments, each task condition was recorded by 3 repeated trials to test the intrasubject variability of the measurements. Indeed, only data that are sufficiently stable across repetitive measurements can give a reliable impression of a person's motor performance.

Materials and Methods

Subjects

Of 4 patients with tetraplegia who were in a stable neurologic condition, 5 hands were selected for reconstructive hand surgery after optimal conservative treatment. The goal of surgery was to improve lateral

prehension or key grip and to stabilize the metacarpophalangeal joints (Table 1).

After surgery each patient underwent 3 weeks of splinting followed by a rehabilitation program that was built up gradually over a 9-week period consisting of intermittent splinting, electrotherapy, hand function training, and myofeedback. All patients were treated 4 times daily 5 days a week.

Equipment

Drawing movements were recorded with a Calcomp 2500 digitizer (Calcomp, Anaheim, CA) and a pressure-sensitive electronic pen (leaving a normal ink trace) connected to a personal computer.²⁰ The position of the moving pen tip was sampled in 2 directions at a frequency of 100 Hz and with a spatial accuracy of ± 0.2 mm. The coordinates of the pen tip were recorded when it was in contact with the digitizer or when it was up to 5 mm above its surface. The signals were filtered by means of a Fast-Fourier analysis using a cut-off frequency of 10 Hz.²⁰ A tape recorder was used in the dual-task condition to aurally present subjects with arithmetic problems. Grip force was measured using a pinch gauge meter with an accuracy of 50 g (0.5 N).

Procedure

The basic task involved the repetitive drawing of short straight lines filling up a 30×10 mm rectangle printed on a piece of paper attached to the digitizer. The rectangles were positioned at a 45° angle with respect to the frontal plane of the body for patients using their right hand or at a -45° angle for patients

Table 1. Subject Characteristics

<i>Case No.</i>	<i>Age (yr)</i>	<i>Gender</i>	<i>ASIA</i>	<i>IHC</i>	<i>Surgical Procedure</i>
1	46	M	D	8:O	IP-1 arthrodesis Zancolli-Lasso
2	21	M	A	3:Cu	IP-1 arthrodesis BR-FPL Deltoid-triceps
3	51	F	A	3:Cu	IP-1 arthrodesis BR-FPL ECRL-FDP
4	19	M(L)	D	7:Cu	IP-1 arthrodesis BR-FPL ECRL-FDP
5	19	M(R)	D	9:Cu	BR-FPL

ASIA, American Spinal Injury Association Impairment Scale; IHC, International Hand Classification; O, ocular; Cu, cutaneous; IP-1, interphalangeal joint of the thumb; BR, brachioradialis muscle/tendon; FPL, flexor pollicis longus muscle/tendon; FDP, flexor digitorum profundus muscle/tendon; ECRL, extensor carpi radialis longus muscle/tendon.



Figure 1. A 30 × 10 mm rectangle for right- and left-handed patients.

using their left hand (Fig. 1). This configuration assured that movements were generated primarily by the wrist joint. The rectangles served as a spatial and directional reference rather than strict boundaries. Every subject was seated at a height-adjustable table in front of the digitizer. The pen was held in a key grip, in some cases assisted by a thickening of the pen. Once used, such an adaptation was re-used at every follow-up assessment. Before each assessment, every subject was allowed a short training period to adapt to the task demands.

Every assessment comprised 3 repeated test series, each consisting of 3 30-second task conditions in a fixed sequence: line drawing (1) with full attention and vision (single task), (2) while simultaneously performing an arithmetic task (dual task), and (3) while wearing a pair of dark goggles (eyes closed). Each trial was preceded by an anticipatory period of 5 seconds after which a tone was used to indicate the start of the registration. In all conditions the tip of the pen was placed on a dotted 30-mm line in the middle of a printed rectangle. Subjects were instructed to make multiple movement strokes within a rectangle as rapidly and fluently as possible after hearing the starting tone. Stops between consecutive strokes had to be prevented. If the pen slipped out of the hand the patient had to pick it up and continue drawing as quickly as possible.

The arithmetic task consisted of 8 single-digit addition problems that could be correct or incorrect (eg, $5 + 3 = 8$, $6 + 4 = 11$). These were presented aurally during the 30-second dual-task registration. The patients had to indicate whether each arithmetic problem was correct by giving true or false responses. Immediately before the first dual-task registration the arithmetic task was practiced and then recorded to obtain its single-task performance.

Line drawing was assessed at 6 consecutive times: before surgery, 6 weeks after surgery (after 3 weeks of splinting followed by 3 weeks of initial hand function training), and at 4 2-week intervals thereaf-

ter. Force measurements were made at the time of the first and last line drawing assessment.

Data Analysis

The multiple movement strokes were automatically segmented on the basis of their velocity minima. Pen down periods were identified on the basis of pen pressure. The mean velocity during these periods was calculated (velocity) as well as the mean number of velocity changes (ie, a velocity <20% of the mean velocity) per centimeter per 30-second trial (dysfluency). Dysfluency served as a measure for temporal accuracy; spatial accuracy was not analyzed. Pen pressure itself was not analyzed because it is not a kinematic parameter.

Statistical Analysis

A 3-way multiple ANOVA was used to assess time (6 assessments) by condition (single task, dual task, eyes closed) and by repetition (3 trials). Specific time and condition effects were further analyzed using paired *t*-tests. *F*- and *t*-values (with degrees of freedom) are the statistical parameters, respectively, representing the found variation divided by the expected variation of the group averages. Intrasubject variability of either kinematic parameter over 3 identical trials was expressed in a coefficient of variation (CV): $CV = SD/mean \times 100$.²² Pearson correlation coefficients tested the relationship between key grip strength and kinematic parameters.

Results

With regard to the movement velocity there was a main effect of time, $F(5,20) = 5.16$ ($p < .005$) and condition, $F(2,8) = 27.17$ ($p < .001$). There was no main effect of repetition or any interaction effect with repetition. Therefore, the results of the 3 identical trials within each assessment were averaged for further analysis. As can be readily seen in Figure 2, the condition effect was related to a consistent degree of visual dependency for line drawing. Across different assessments there was a significant difference between single-task and eyes closed performance, $t(4) = 6.23$ ($p < .005$), and between dual-task and eyes-closed performance, $t(4) = 4.52$ ($p < .05$), but no difference between single-task and dual-task performance. Over different conditions there was a 23% increase in movement velocity between the preoperative and first postoperative assessment, $t(4) = 2.99$ ($p < .05$). Between the first and last postoperative assessment an additional 16% overall velocity in-

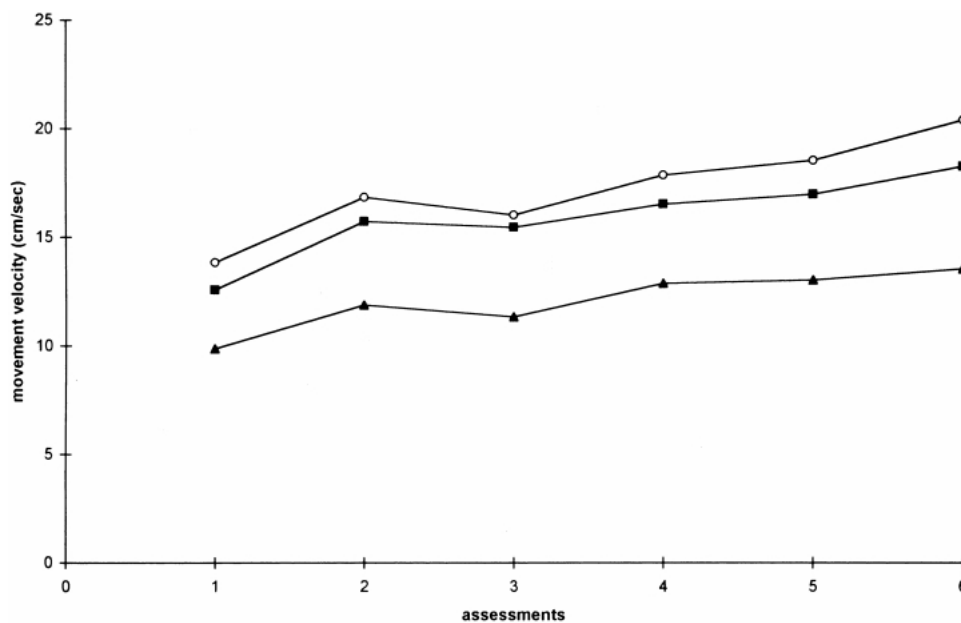


Figure 2. The mean values (5 cases) of movement velocity across 6 assessments. ○, Single task; ■, dual task; ▲, eyes closed.

crease could be measured that did not reach significance. With regard to movement dysfluency there was merely a main effect of condition, $F(2,8) = 11.05$ ($p < .01$), reflecting reduced movement control as a result of visual deprivation. The results averaged over repetitions are presented in Figure 3.

The CVs calculated over repetitive measurements and averaged over all cases are presented in Table 2 for 3 assessments (before surgery and first and last

after surgery) and different task conditions. All CV values showed good stability for both movement velocity and dysfluency, ie, a percentage well below 20.

Grip strength increased in all patients as a result of reconstructive hand surgery (Table 3). No significant correlation was found, however, between the change in grip strength and the change in either kinematic parameter before or after surgery. Figure 4 presents a plot of difference in grip force between the preop-

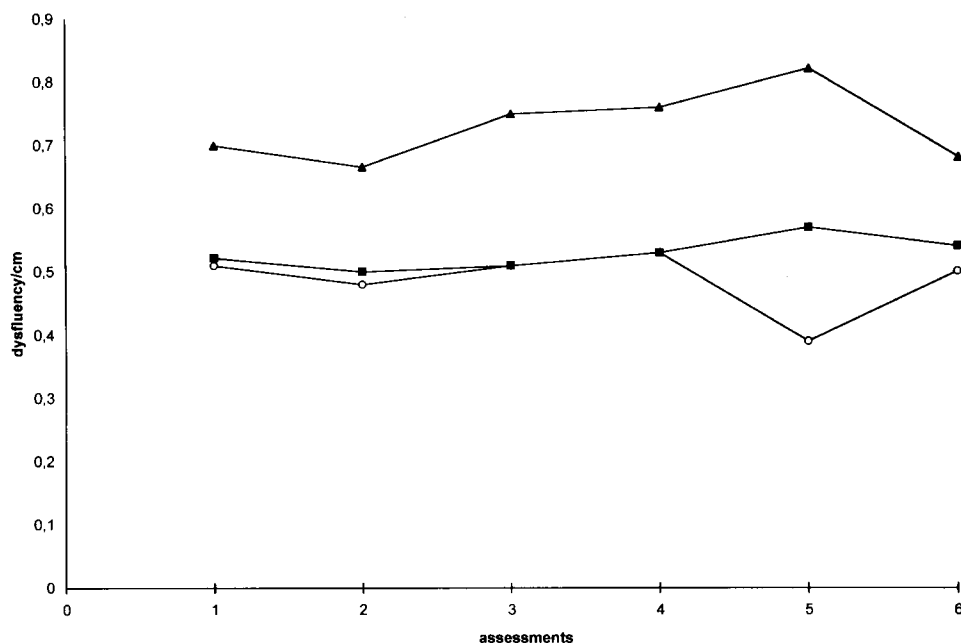


Figure 3. The mean values (5 cases) of dysfluency across 6 assessments. ○, single task; ■, dual task; ▲, eyes closed.

Table 2. Coefficients of Variation (%)

Condition	Assessments		
	1	2	6
Movement velocity			
Single task	7.7	6.3	4.0
Dual task	6.0	5.7	3.3
Eyes closed	7.1	6.2	5.2
Movement dysfluency			
Single task	5.4	8.6	6.8
Dual task	9.2	7.9	5.7
Eyes closed	10.9	11.2	8.6

erative and last postoperative assessment versus changes in line drawing for each individual case.

Discussion

This study used a kinematic approach to the assessment of manual skill in relation to reconstructive hand surgery in tetraplegic patients. More specifically, we investigated whether a line drawing task performed on a digitizer using conditions of different complexity could produce stable and meaningful data to objectify functional improvement after surgical key grip reinforcement.

The low CV values of both movement velocity and dysfluency indicated a good stability of line drawing performance at all times in all conditions. The absence of any effect of repetition precludes a significant learning effect or influence of fatigue in the short term. Data obtained from other patient groups have shown that there also are no learning effects with these simple line drawing tasks in the long term, eg, at 2-week intervals. In addition, possible ceiling effects are unlikely because healthy subjects show a mean movement velocity during the same tasks of 18.8 ± 5.9 with eyes open and of 13.8 ± 4.6 with the eyes closed. Hence, the reliability and responsiveness of the proposed kinematic assessment can be considered sufficient.

The fact that no association was found between change in key grip force and change in kinematic parameters may seem counterintuitive assuming that force improvement is the critical factor in producing better movement control. It is quite possible, however, that other factors (eg, deep sensibility, cognition, muscle coordination) play a critical role in the ability to use improved grip force for controlling a pen while drawing. This independency of force and controlling such force

during complex movements seem to stress the value of assessing manual skill (the ability to direct force) besides isolated hand functions. Another reason for the lack of association between the change in grip force and change in movement control may be related to the unreliability of measuring peak force in subjects with severely impaired hand functions.

Movement velocity appeared sensitive to the effect of key grip reinforcement, whereas dysfluency remained unaffected across time. This pattern of results suggests a true improvement of drawing skill following hand surgery and precludes a speed-accuracy tradeoff. Both movement velocity and dysfluency were consistently affected by visual deprivation. This detrimental influence of visual deprivation on patients' motor performance is easily understood considering the influence of vision on the control of hand and finger movements, even in healthy subjects.²⁶ It is remarkable, however, that not even a temporary change in the effect of visual deprivation on line-drawing skill was found after hand surgery. The same accounts for the lack of influence of concurrent arithmetic performance. These results might suggest a rapid central reorganization leading to a considerable level of automatic and proprioceptive control of hand movements. Yet, the data available in this study are too limited to allow definitive conclusions on this matter. Earlier work has clearly demonstrated the value of using various task complexities for monitoring learning and adaptation processes following peripheral damage to the neuromuscular system.²²⁻²⁴

It is interesting to note that the effect of functional hand surgery and initial hand function training on movement velocity was about twice as large as the effect of rehabilitation 6 to 12 weeks after surgery. Firm conclusions about the relative effectiveness of different parts of the treatment cannot be drawn based on this study, however, due to insufficient control of confounding factors.

Table 3. Grip Strength (g)

Case No.	Assessment	
	1	6
1	1,000	1,300
2	0	770
3	50	275
4	150	2,250
5	1,400	2,500

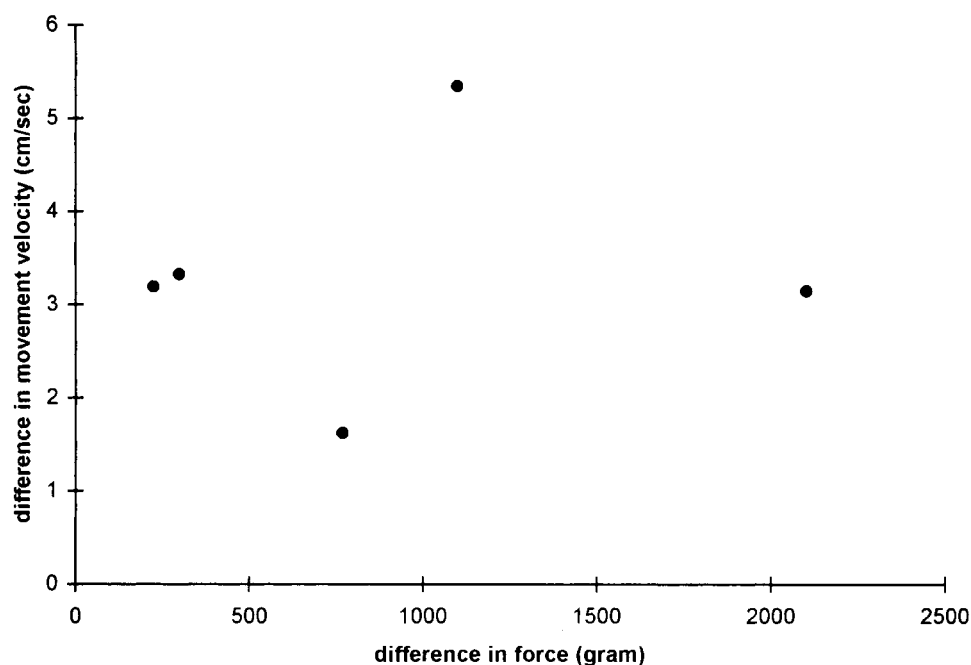


Figure 4. Correlation between change in force and change in movement velocity before and after surgery.

The proposed procedure for the kinematic assessment of line-drawing skill in tetraplegic patients before and after reconstructive hand surgery provides stable data that add to the measurement of isolated grip strength. It is applicable in all tetraplegic patients with a minimal capacity to hold an electronic pen in a lateral prehension grip if necessary after thickening of the pen. This kinematic assessment procedure will be further used for evaluating specific treatments aimed at improving manual skills in tetraplegic patients as well as in other neurologic patients with minimal hand function. Such a kinematic analysis of fine motor control also may allow the clinician to better monitor functional performance and specify treatment goals in individual patients.

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