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Kinematics of prehension and pointing movements in C6 quadriplegic patients

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Aims: C6 quadriplegic patients lack voluntary control of their triceps muscle but can still perform reaching movements to grasp objects or point to targets. The present study documents the kinematic properties of reaching in these patients.
Materials and methods: We investigated the kinematics of prehension and pointing movements in four quadriplegic patients and five control subjects. Prehension and pointing movements were recorded for each subject using various object positions (ie different directions and distances from the subject). The 3D motion was analyzed with Fastrack Polhemus sensors.
Results: During prehension tasks the velocity profile of control subjects showed two peaks (go and return); the first velocity peak was scaled to the distance of the object. In quadriplegic patients there was a third intermediary peak corresponding to the grasping of the object. The amplitude of the first peak was slightly smaller than in control subjects. Velocity was scaled to the distance of the object, but with a greater dispersion than in control subjects. Total movement time was longer in quadriplegics because of the prolonged grasping phase. There were few differences in the pointing movements of normal and quadriplegic subjects. The scapula contributed more to the reaching phase of both movements in quadriplegic patients.
Conclusion: In spite of some quantitative differences, the kinematics of the hand during reaching and pointing in quadriplegic patients are surprisingly similar to those of control subjects.
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Keywords: spinal cord injury; tetraplegia; prehension; pointing movements; reaching; 3-D motion analysis

Introduction

Patients with a cervical spinal cord injury at the C6 motor level have minimal loss of strength in the shoulder and elbow flexor muscles. The triceps, a C7 level muscle that is considered to be the primary elbow extensor,[1,2] is paralyzed. These subjects have no voluntary control of the muscles of the hand, but still have wrist extensors that allow prehension by 'tenodesis': an active dorsal flexion of the wrist leading to passive finger flexion. Daily clinical experience indicates that quadriplegic patients who have lost their triceps muscle activity can still extend their elbow[3,4] and point to targets or grasp objects, even when these are placed well away from them. The current hypothesis is that they use a combination of external rotation of the shoulder, gravity, and inertia of the arm to achieve this 'passive' elbow extension. However, the arm movements of quadriplegics have never been systematically studied using quantitative methods. The present study was therefore done to record the 3D movement of the hands of C6 quadriplegic patients during prehension and pointing movements, and to analyze the efficiency of the motor strategies they develop in trying to compensate for their impairment. This stage is necessary for further investigations of the coordination between joints during reaching.[5] Our long term intention is to use such quantitative methods to analyze and monitor functional improvements after tendon transfer surgery and rehabilitation.

Materials and methods

Population

We studied four post-traumatic quadriplegic patients (see the main clinical data in Table 1). The study was approved by the local ethics committee, and the patients having volunteered to take part in the study,

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were informed of its aims. The mean age of the patients was 29 years (range 26–34 years). All were right-handed, and their right arms were studied. All had a C6 sensitive and motor-complete SCI corresponding to grade A on the ASIA classification.[6] They were at least 5 months post-injury (range 5–19 months). Three of them had been involved in motor vehicle accidents and one had had a diving accident. They had poor voluntary control of their triceps with a manual muscle test of 1 to 2/5.[7] One patient had orthopedic limitations of the shoulder (5° external rotation, 80° abduction), at the elbow (10° flexion, −30° pronation) and of the wrist (45° palmar flexion). The three other patients had no joint limitations.

Five healthy right-handed subjects (four women and one man, 22–52 years old, mean age 35) served as controls. None had a history of neurological or orthopedic disorders.

Experimental set-up
All the subjects were seated in a wheelchair with their upper right arm supported on a table (see Figure 1A). The back of the wheelchair was inclined (about 10°) and a strap was placed across the chest and secured to the chair to minimize forward movements of the trunk. Lateral splints fixed on the wheelchair prevented lateral movements of the trunk. The left arm was bent in a sling so that subjects could not push or pull the table to help them move.

Six lines centered on a horizontal projection of the subject's shoulder were drawn on the table (Figure 1B). The lines were 30° apart, starting from the right (0°) to the line at 150° on the left side of the subject. Target positions along each diagonal were determined for each subject as a function of the length of their extended upper limb, and marked by adhesive tape. Short prehension distances corresponded to the level of the wrist, while long prehension distances corresponded to the level of the metacarpo-phalangeal joint. The object used for prehension was a cardboard cone placed on a 10 cm base to prevent the subjects sliding their hand along the table. Pointing movements were made with a pointer (10 cm wooden stick) fixed to the back of the hand between the second and third fingers. The target (2 cm square) was either placed 10 cm above the table (low pointing movements) or fixed 20 cm above the level of the acromion (high pointing movements). The pointing distance was slightly beyond the reach of the pointers.

The resting hand position on the table was indicated by a red spot placed 10 cm from the midline and 15 cm from each subject's abdomen (Figure 1B). Because the initial position was not centered on the horizontal shoulder projection, the distance of the movements towards the targets varied with the direction.

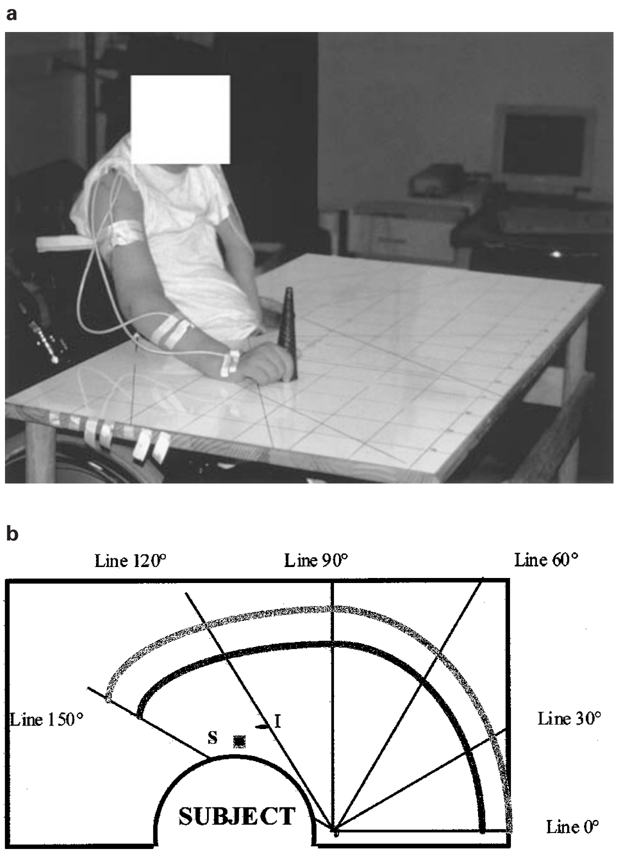

Figure 1 (**A**) A quadriplegic patient sitting at the table during a prehension task. (**B**) Diagram of the table with the STS transmitter (S), the initial position of the hand (I), the six lines and the two arcs of prehension (short distance prehension, lower arc; long distance prehension, top arc)

Table 1 Quadriplegic patients – main clinical data

Patient	*MAR*	*MOS*	*SIM*	*CAD*
Present age (years)	30	34	26	26
Gender	M	M	M	M
Dominant side	Right	Right	Right	Right
Time since injury	6 months	10 months	5 months	19 months
Arm studied	Right	Right	Right	Right
Manual muscle test	1/5	1/5	1/5	2/5
Motor ASIA score	17	21	20	22
Orthopedic status	Normal	Impaired	Normal	Normal

Procedure

The subjects performed four sets of experiments: prehension of objects placed at short or long distances, and low and high pointing. Each set included three to five successive movements in each of the six directions, in the same order for all the subjects: 0°; 60°; 120°; 150°; 90°; and 30°. For prehension, subjects were instructed to move their hand from the initial position to grasp the cone and return it to the starting point. For pointing movements they were asked to position the pointer in the direction of the target and to maintain a stable position for 2 s. There was no emphasis on the speed or accuracy of movements. Missed movements were repeated.

The subjects were told to relax between the movements with their hand resting in the initial position. No period of practice was allowed before the recordings. At least 72 (quadriplegics) to 120 (control) movements were studied in each subject. The recording session lasted about 60 min.

Movement recording

The 3D motion was analyzed with Fastrack© Polhemus sensors (Spatial Tracking System VPL©). This system uses an electromagnetic field generated by a transmitter to determine the position and orientation of four remote sensors using a 30 Hz recording frequency. The values were digitized by an analog-digital converter and transmitted on-line to a PC. We analyzed the 3D positions of two sensors, one attached to the dorsum of the hand (middle part of the third metacarpal bone) and one to the ipsilateral acromion.

Data processing

The effectiveness of the upper-limb kinematics was analyzed from the trajectory of the hand sensor which was considered to be the end-point of the multi-jointed limb. The acromion sensor was used to check the movement of the shoulder girdle. Because the thorax could not move, displacements of the acromion sensor reflected movements within the scapulo-thoracic joint. The 3D trajectories of the two markers were determined by observation of their sagittal and horizontal projections, and by analysis of their tangential velocity profiles. The onset of the movement was defined as the first sample of the hand velocity profile above a threshold of 0.01 m/s. The peak velocity of the hand sensor was determined during the reaching movement. The total duration of movement (MT) was measured between the onset of the movement and the time of return to the resting hand position. We also measured the duration of the ballistic phase of the reaching movement (time BT until the peak velocity had fallen by half) and the duration of reaching and grasping (time GT until the onset of return movement).

Statistical analysis

The means of three to five trials were calculated for each subject in each situation. Statistical analyses were performed using analysis of variance (ANOVA), covariance analysis (ANCOVA), regression analysis, and Student's *t*-test. A significance level of 0.05 was chosen.

Results

Prehension movements

Control subjects The trajectory of the hand towards the object was smooth and gently curved in the vertical (gravitational) dimension (Figure 2A). The profile of the tangential hand velocity had a bell-shaped pattern with two peaks, one for reaching and one for return. The movement of the scapula was rather limited, as shown by the short trajectory of the acromion sensor. Similar patterns were obtained for all directions of

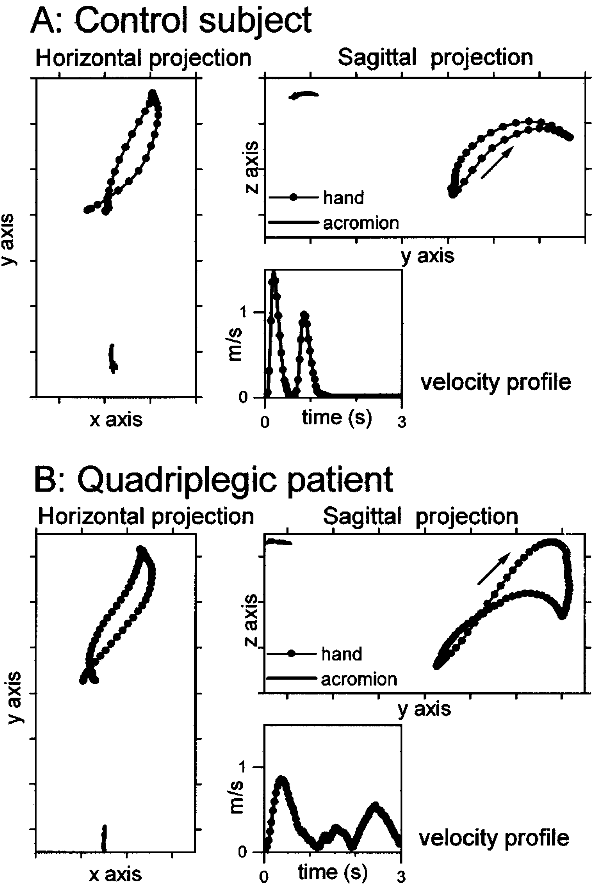

Figure 2 A representative trial of one control (**A**) and one quadriplegic (**B**) subject showing movement of prehension on the 90° line (long distance prehension). Hand and acromion trajectories are as observed from overhead (horizontal projection, X and Y axis, left) and the sagittal view (Y and Z directions, right). Down: tangential velocity profile of the hand

movement in the short and long distance prehension. Peak hand velocity and total duration of the movement are shown in Tables 2 and 3.

Quadriplegic patients The trajectory of the hand movements made by quadriplegic patients differed in two respects from those made by the control subjects. First, the reaching movement appeared to be higher, with a greater curvature in the sagittal plane (Figure 2B). Second, a smaller velocity peak, corresponding to the shaping of the hand to grasp the cone, was inserted between the reaching and the return movement peaks. This pattern was observed for all the target directions and the two distances.

The peak velocity of reaching movements was slightly smaller in quadriplegic patients than in control subjects (see Table 2). This difference was just significant for short distance prehension, but not for long distance prehension. One patient (MOS) had smaller peak hand velocity than the others (see Figure 3). The total movement time was much longer in quadriplegic patients than in control subjects (see Table 3). This difference was mostly due to the delay in grasping and not to the reaching part of the movement (Figure 4).

The maximum height of the reaching movements was significantly greater in the group of quadriplegic patients (0.37 m) than in control subjects (0.26 m for long distance and 0.27 m for short distance prehension; $P<0.0001$).

The displacement of the acromion sensor was greater in quadriplegic patients than in control subjects (t-test, $P=0.0015$ for short distance prehension and $P=0.0152$ for long distance prehension).

Pointing movements

Control subjects The trajectory of the hand during low (10 cm above the table) or high (20 cm above the acromion level) pointing movements was roughly straight with a smooth bell-shaped velocity profile (Figure 5A). There was little displacement of the acromion sensor, even for targets above the level of the shoulder. Peak hand velocities are shown in Table 2. For high pointing movement, the control subjects held the hand at the level of the target (0.203 ± 0.005 m above the level of their acromion).

Quadriplegic patients The hand trajectories of quadriplegic subjects during pointing were not qualitatively different from those of control subjects (see Figure 5B). However, the peak velocity of the hand was significantly smaller (see Table 2).

The maximum height of the hand trajectory during low pointing movements was lower in quadriplegic patients than in control subjects ($F=17.6$, $P<0.0001$). Quadriplegic patients held the hand significantly below the instructed 20 cm level (0.127 ± 0.006 m, $F=78.7$, $P<0.0001$).

The displacement of the acromion sensor was greater in quadriplegic patients (t-test, $P=0.0072$ in low pointing movements and $P=0.045$ in high pointing movements).

Influence of object location

Amplitude of the velocity peak The peak velocity of reaching during prehension by control subjects varied with the location of the object (ANOVA:

Table 3 Movement time (with standard deviation)

	Long dist. prehension	*Short dist. prehension*
Control	1.818 s (±0.254)	1.809 s (±0.450)
Quadriplegics	3.303 s (±1.082)	3.120 s (±0.849)
P value	<0.0001	<0.0001

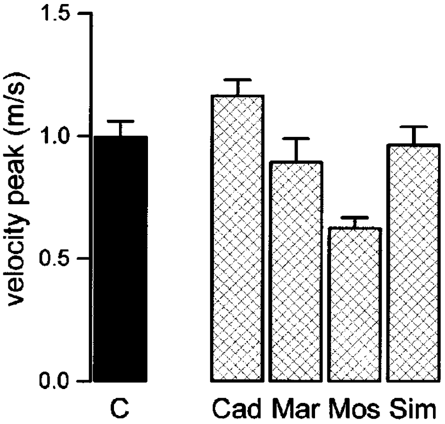

Figure 3 Peak hand velocity of the four quadriplegic patients during long distance prehension (on the right) and mean value for control subjects in the same conditions (C)

Table 2 Peak hand velocity (with standard deviation) in control and quadriplegic subjects

	Short dist. prehension	*Long dist. prehension*	*Low pointing*	*High pointing*
Control	1.080 (±0.311) m/s	1.194 (±0.312) m/s	1.081 (±0.313) m/s	1.467 (±0.250) m/s
Tetraplegics	0.923 (±0.247) m/s	1.039 (±0.282) m/s	0.825 (±0.251) m/s	1.099 (±0.312) m/s
P value (*t*-test)	0.0496 (S)	0.064 (NS)	0.0022 (S)	0.0002 (S)

F = 18,497, $P<0.0001$ for the long distance set of movements; F = 20.202, $P<0.0001$ for the short distance set of movements). The distance of the target was not the same in each direction, so this finding could be due to the variation in the direction of the object by reference to the shoulder, or to the variation in the distance between the initial hand position and the object. There was a significant linear relationship between the distance and the velocity peak in all the subjects for both sets of movements (Figure 6A). ANCOVA demonstrated that the relationship between the movement distance and the peak velocity was independent of the differences between subjects (ANCOVA F = 259, $P<0.0001$ for the short and F = 119.2, $P<0.0001$ for the long distance set of movements). The variation in the velocity peak with the location of the object followed the same trend in quadriplegic patients but was significant in only three patients for the long distance prehension (Figure 6B) and in two patients for the short distance prehension. ANCOVA showed that the velocity peak was significantly correlated with object distance, independently of the factor subject (F = 36.8, $P<0.0001$ and F = 21.2, $P<0.0001$ respectively).

Height of the trajectory The maximum height in the reaching phase of prehension movements in control subjects varied with the location of the objects. It was higher for external right locations (Figure 7A, ANOVA: F = 7.3, $P = 0.003$ for long distance; F = 17.1, $P<0.0001$ for short distance prehension). Quadriplegic patients always reached with a high trajectory, whatever the direction (Figure 7B).

The maximum height of low or high pointing movements (Figure 7C,E) made by control subjects did not depend on object location. Surprisingly,

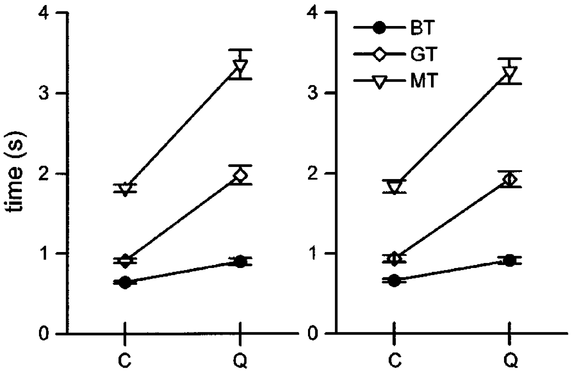

Figure 4 Timing of prehension movements made by control subjects (C) and quadriplegic patients (Q). BT: ballistic time (time taken for velocity to decrease by half). GT: reaching and grasping time (time until the onset of return movement); MT: total movement time. On the left is the diagram for a short distance and, on the right, a long distance prehension

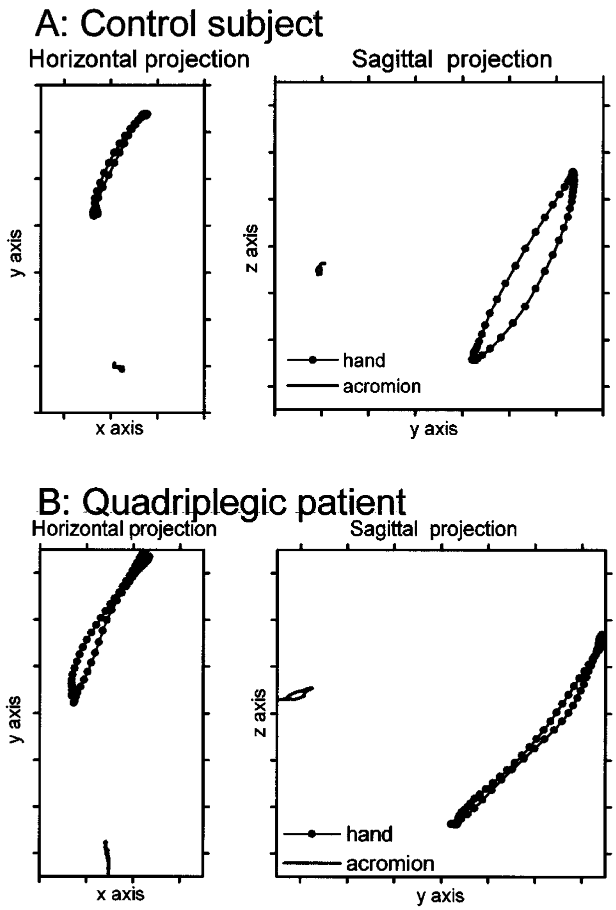

Figure 5 A representative trial of one control subject (**A**) and one quadriplegic patient (**B**); movement of high pointing on 90° diagonal. Hand and acromion trajectories as observed from overhead (horizontal projection, X and Y axis, left) and sagittal view (Y and Z directions, right)

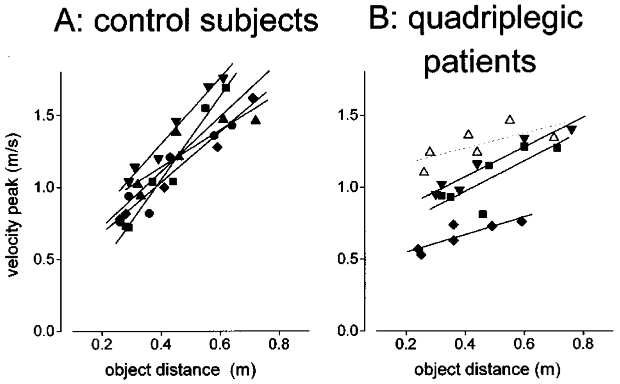

Figure 6 Individual linear relationship between the distance of the object and the velocity peak in inner and outer prehension circles. (**A**) Control subjects. (**B**) Quadriplegic patients. Each symbol represents the mean of three to five movements made by one subject. The regression lines are indicated. Black symbols and continuous lines indicate a significant relationship

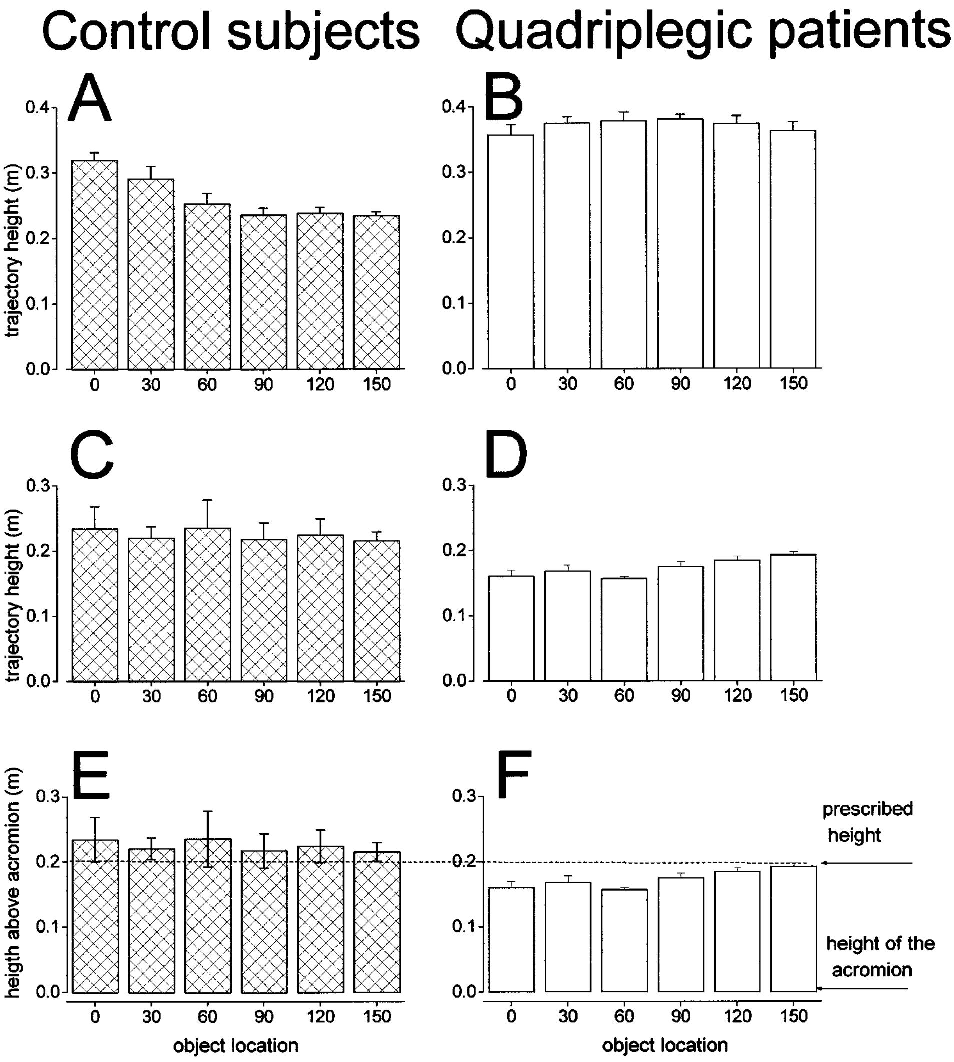

Figure 7 Maximum height of the hand trajectory for the different locations of the object. Each bar represents the mean of three to five movements; the standard error of the mean is indicated. (**A,C,E**) control subjects. (**B,D,F**) quadriplegic patients. (**A,B**) prehension movements. (**C,D**) low pointing movements. (**E,F**) high pointing movement. The maximum height of the trajectory is expressed by reference to the height of the acromion

quadriplegic patients made pointing movements whose height varied with object location. This was more evident for high pointing movements (Figure 7F, ANOVA: $F=13.7$, $P<0.001$) than for low pointing movements (Figure 7D, ANOVA: $F=3.4$, $P<0.03$). In high pointing movements, the height of the hand was highest for the object located in the internal left part of the workspace, where it approached the prescribed height (20 cm above the level of the acromion) and lowest for the external right object location.

Displacement of the acromion sensor The displacement of the acromion sensor varied with the location of the object in control subjects. It was larger for left object locations where the hand movements crossed the midline (in long distance prehension, the mean values of the displacement of the acromion was 0.028 m on the right of the subjects and 0.071 m on the left). The effect of object location was significant in all the four types of movements ($F=8.9$, $P<0.0001$ for long distance prehension; $F=5.2$, $P=0.002$ for short distance prehension; $F=16$, $P<0.0001$ for low pointing; $F=7.7$, $P=0.002$ for high pointing). This effect was due not only to distance because ANCOVA with movement distance as a cofactor gave irregular and variable results depending on the type of movement.

The amplitude of the acromion displacement followed the same trend in quadriplegic patients but the effect of object location was significant only for low pointing movements ($F=4.6$, $P=0.006$).

Discussion

New insights into control of prehension by normal subjects

The hand trajectories of control subjects followed a gently curved path and had a smooth velocity profile scaled to movement distance. Grasping the object did not cause any recognizable delay, probably because subjects prepared their grasp while reaching.[8] These observations are consistent with earlier descriptions in which the movement workspace was restricted to the area in front of the subjects,[9,10] or limited to a horizontal plane.[11] These features are characteristic of a programmed hand movement in which the control of upper limb coordination anticipates the biomechanical perturbations of the movement itself.[8,12] In addition, the maximum height of the hand trajectory was greater for the objects located externally on the right. This suggests that the control of the reaching movement in normal subjects incorporates some constraints due to grasping because the hand has to be raised above the object before grasping when it is located externally.

Motor impairment and its compensation in quadriplegic patients

Previous studies on motor control in quadriplegic patients Few studies have been done on the kinematic properties of the arms of C6 quadriplegic patients. Popovic *et al*[13,14] analyzed the kinematics of the shoulder and elbow joints of C6 quadriplegic patients and control subjects during pointing movements in the horizontal plane. They observed that the movement in control subjects was due to a synergy between elbow and shoulder rotations. Quadriplegic patients were slower, and started the reaching process by a shoulder motion which preceded the elbow movement. Wierzbicka *et al*[15,16] observed that fast elbow flexion movements took longer and were less accurate in C6 quadriplegic patients than in control subjects. This shows that the lack of an antagonist disturbs fast goal-directed movements. The experimental apparatus used for these studies was quite constraining and, unlike the present study, did not allow extrapolation of the conclusions to physiological movements.

Grasping strategy The most prominent feature in the movement trajectories recorded in quadriplegic patients is the introduction of a smaller third velocity peak between the reaching and return movements. This peak represents the hand movement during the compensatory grasping strategy by 'tenodesis', a strategy in which quadriplegic patients make a wrist extension to close the fingers passively for grasping. This pattern suggests that reaching and grasping are sequentially planned, as compared with control subjects among whom the grasping is prepared during reaching.[8] However, we cannot exclude the possibility that the delay in grasping results from the need to achieve full elbow extension before contracting wrist extensors, which may act as elbow flexors because they have a humeral insertion.

Efficiency of hand transport for reaching The efficiency of the arm coordination, as it is measured by the velocity peak of the hand during reaching or pointing, was similar in quadriplegic patients and in control subjects. What difference there was (not statistically significant in all the conditions) may have been due to one subject who had joint limitations (MOS). In addition, quadriplegic patients were able to scale the peak hand velocity to the distance of the object. This relationship has never previously been demonstrated in patients with such neurological impairment.

However, the movement patterns of the two groups of subjects were quite different. We analyzed the hand trajectory to explore the mechanism of the motor compensation which allows the efficient transport of the hand despite paralysis of the elbow extensors. For pointing movements in the external part of the work space, quadriplegic patients made lower trajectories than control subjects; this can be attributed to an insufficient compensation for the paralysis of the triceps. By contrast, they made higher trajectories than control subjects for prehension movements, whatever the object location. Thus, high reaching trajectories for grasping can be attributed to the acquisition of a new motor strategy to compensate for grasping impairment, not to compensate directly for triceps paralysis. Quadriplegic patients seemed to launch their hand above the object, which was then passively grasped as the hand was lowered. A similar strategy has been observed in hemiparetic patients with a predominantly distal motor impairment.[17] It is well known from prehension studies in normal subjects that reaching and grasping are tightly coupled, and that altering the grip by varying the size of the object affects the kinematics of reach.[10,18–20] The present observations extend this notion for a wider work space, and to the case of quadriplegic patients in which the grip itself is impaired.

Shoulder girdle and arm coordination for reaching The quadriplegic patients made smooth, accurate and relatively fast reaching and pointing hand movements. This means that they have acquired a new coordination for movement control despite the triceps paralysis. This coordination probably includes the increased use of proximal muscles and of gravity to compensate for the paralysis of the elbow extensors. Indeed, the amplitude of scapular displacement in quadriplegics was much greater in both prehension and pointing movements; in control subjects, the scapula made no significant contribution to hand transport, probably because targets were within arm's length.[21] A movement of the acromion in the present experiment reflected a movement in the scapulo-thoracic joint, because the thorax was blocked. Reaching in quadriplegics probably also involves increased movements in the scapulo-humeral joint. Generally speaking, the present results support the hypothesis that the CNS restores hand kinematics by using different angular configurations, while the dynamics of the upper extremity are completely changed. This suggests that there is a kinematic representation of movement at higher levels which does not take into account the mechanical nature of the actual effector.[22]

Clinical implications

One SCI individual had a reduced range of motion in the shoulder, elbow and wrist. He had the same neurological level damage as the others. This man had difficulties in performing his movements and gave quite different kinematic results. His hand was more hesitant and the trajectories were less reproducible. Peak hand velocity was lower in all conditions, and displacement of the acromion was more important. As he had external shoulder rotation stiffness, he used his scapulo-thoracic joint to grasp or to point to objects in the right space. These results emphasize the importance of preventing orthopedic diseases in quadriplegic patients.

One of the four patients underwent the protocol 6 months post injury, and then 10 months later. The results of the second evaluation did not show large differences compared to those of the first. Global trajectory and hand velocity were the same. Displacement of the acromion sensor was slightly less, but the strategy was the same. This suggests that new strategies may have been learned during the first months following injury, and did not change later. This emphasizes the importance of very early rehabilitation in quadriplegic subjects. This should be confirmed by studying other subjects.

Future prospects

The angles of the upper limb joints need to be analyzed to test the hypothesis that quadriplegic patients acquire new coordination. The present set-up will allow the computation of thoraco-scapular, scapulo-humeral, elbow and wrist angles.[5] It will then be possible to investigate how quadriplegic patients can adapt the elbow-shoulder synergy described in control subjects during pointing[21,13] and prehension movements.[23,24]

These stages of investigation are necessary to obtain a better understanding of the process of functional improvement during rehabilitation therapy, and after tendon transfers. Surgery of the upper arm, in particular the transfer of the posterior deltoid to triceps tendon, has been shown to produce a significant improvement of function in quadriplegics and is currently proposed for these patients.[25] Muscle transfers offer a restoration of active elbow extension, and active and strong finger flexion in simple tasks. It is now important to investigate how the transferred muscle is activated and to explore its biomechanical efficiency during physiological gestures. A better understanding of how the central nervous system controls and modifies the kinematic characteristics of movement is important for improving the clinical care of quadriplegic patients.

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