ORIGINAL ARTICLE

Kinematic characteristics of tenodesis grasp in C6 quadriplegia

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Study design: Descriptive control case study.

Objectives: To analyze the kinematics of tenodesis grasp in participants with C6 quadriplegia and healthy control participants in a pointing task and two daily life tasks involving a whole hand grip (apple) or a lateral grip (floppy disk).

Setting: France.

Methods: Four complete participants with C6 quadriplegia were age matched with four healthy control participants. All participants were right-handed. The measured kinematic parameters were the movement time (MT), the peak velocity (PV), the time of PV (TPV) and the wrist angle in the sagittal plane at movement onset, at the TPV and at the movement end point.

Results: The participants with C6 quadriplegia had significantly longer MTs in both prehension tasks. No significant differences in TPV were found between the two groups. Unlike control participants, for both prehension tasks the wrist of participants with C6 quadriplegia was in a neutral position at movement onset, in flexion at the TPV, and in extension at the movement end point.

Conclusion: Two main kinematic parameters characterize tenodesis grasp movements in C6 quadriplegics: wrist flexion during reaching and wrist extension during the grasping phase, and increased MT reflecting the time required to adjust the wrist's position to achieve the tenodesis grasp. These characteristics were observed for two different grips (whole hand and lateral grip). These results suggest sequential planning of reaching and tenodesis grasp, and should be taken into account for prehension rehabilitation in patients with quadriplegia.

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INTRODUCTION

Human prehensile movement, one of the fundamental hand functions, is dramatically disturbed after cervical spinal cord injury.^{1,2} Indeed, individuals with C6 quadriplegia retain control of elbow flexor and wrist extensor muscles but lose active extension of the elbow and the ability to perform active prehension movements. These patients can, however, learn a tenodesis grasp after extensive physical rehabilitation, allowing them to perform compensatory passive prehension.^{2–4} Tenodesis grasp involves extension of the wrist (extensor carpi radialis longis and brevis) and can result in two different grasps: a passive whole hand grip due to finger flexor shortening and a passive lateral grip due to flexor pollicis longus shortening.^{1,2,4,5}

The kinematics of normal human prehensile movements have been extensively studied since Jeannerod.^{6–9} Indeed, healthy individuals exhibit two prehension components: a reaching phase involving the shoulder, elbow and wrist, and a grasping phase requiring both active finger closure and the opposition of the thumb with the other fingers.⁶ These two phases of healthy human prehensile movements are coupled,^{6–9} as shown by the fact that the maximal grip aperture occurs at the moment of peak deceleration,⁶ which itself occurs at a fixed time, 60–70% of the reaching phase.⁷

Reach-to-grasp movements in individuals with C6 quadriplegia show a series of important kinematics differences compared with

healthy control participants. (i) Concerning the reaching phase, participants with C6 quadriplegia have longer MTs^{10–12} and smaller velocity peaks (PV).^{11–13} Compensatory movements involving proximal upper limb joints during the reaching phase have also been reported. Compensatory movements of the scapula^{11,12,14} and trunk^{12,13} are sometimes used to achieve elbow extension. Muscle activation differences during the reaching phase of reach-to-grasp movements have also been shown in participants with C6 quadriplegia, with isolated activity in the agonist muscles (shoulder and elbow muscles flexors, wrist muscle extensors) without any accompanying antagonist muscle activation.^{15,16} (ii) kinematic differences during the grasping phase are less frequently reported than reaching phase differences. Tenodesis grasp has been associated with more wrist extension,¹⁷ increased wrist height when a glass was grasped,¹⁸ additional velocity peaks^{11,12} and forearm supination during manipulation of the grasped object, showing that participants with C6 quadriplegia use gravity to secure the grasp.¹² (iii) Hoffman *et al.*¹⁷ studied wrist height and trajectories in participants with C6 quadriplegia and reported that, in contrast with healthy control participants, the reaching and grasping phases were performed sequentially. Despite having atypical kinematic profiles during reach-to-graph movements, participants with C6 quadriplegia have relatively smooth movement trajectories during

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reach-to-grasp movements,¹⁴ suggesting that their compensatory movements are efficient. Interestingly, the kinematic characteristics of the tenodesis grasp have never been reported using wrist movements in the sagittal plane.

In this study, a detailed kinematic analysis of the tenodesis grasp was performed in four participants with C6 quadriplegia as well as four age-matched healthy control participants. The tasks examined were a pointing task and two daily life prehension tasks involving two distinct grips (whole hand and lateral grip).

MATERIALS AND METHODS

Population

Four chronic stable stage patients (after C6 spinal cord injury), mean age 27.5 (s.d. 8.3), and four healthy control participants (university students without any history of neurological or orthopedic disease), mean age 29.5 (s.d. 5.0) were included in the experimental groups after the local ethics committee (CPP 2009-051 B) had given its approval. All participants were right-handed based upon the Edinburgh questionnaire. The mean ASIA (American Spinal Injury Association) motor score was 24.5 (s.d. 1.9). Individual data are summarized in Table 1. When they were tested, all participants with C6 quadriplegia were able to reach and grasp an object using tenodesis grasp in daily life as this grasp had previously been learnt during intensive physical and occupational therapy sessions. Upper limb range of motion assessment using a goniometer showed no limitation for the shoulder, elbow, wrist and finger joints in either group. Muscle tonus was assessed using the Ashworth modified scale, no spasticity was found (score: 0/4) in the C6 quadriplegics.

Experimental set-up

Each participant sat in his (her) own manual wheelchair (participants with C6 quadriplegia) or in a standard wheelchair (control participants), in front of the experimental set-up. The back of the wheelchair was tilted backwards (about 10°) and a strap was placed across the chest and secured to the chair to minimize forward movements of the trunk. The table was 73 cm high and the mean height of the seat was 54 cm. All participants kept their left arm on their

left leg while their right index finger was positioned at the starting position, which was 13 cm from their chest in the mid-sagittal plane (Figure 1).

Procedure

After a 5-s resting period, the participants used their right upper limb to perform either a pointing or a grasping movement according to a verbal command given by the experimenter. All movements were self-paced and performed without any training before the kinematic recordings. In the pointing task, the participants were asked to point as accurately as possible to a target. The target was either aligned with the mid-sagittal plane (Center) or shifted 30° toward the right space (Right; Figure 1a). Twenty-two pointing movements were performed toward each target in a predetermined order so that participant anticipation was limited (Figure 1).

In the grasping task, the participants were asked to grasp two objects placed in the mid-sagittal plane (Figure 1b): (i) a 7-cm diameter artificial apple was used to test the whole hand grip; (ii) a vertical floppy disk rotated 45° laterally was used to assess the lateral grip. Each object was grasped in a separate block and each block consisted of 11 grasping movements. If the participant failed to grasp the object on a given trial, then the same movement was repeated. The whole procedure lasted about 60 min and a total of 44 movements were performed.

Movement recording

Movements of the right upper limb were recorded using a 3D motion analysis system at a sampling rate of 50 Hz. The same experimenter placed the marker set using boney palpation. In the pointing task, three reflective markers were placed on the index finger, wrist and elbow. In the grasping task, 10 markers were placed on the following sites: (i) the dorsal surface of the first phalanx of the thumb, (ii) the dorsal surface of the second phalanx of the index finger, (iii) the dorsal surface of the second metacarpal bone head, (iv, v) the two styloid processes, (vi) the middle third dorsal part of the radius bone, (vii, viii) the two epicondyles, (ix, x) on the surface of both the medial and ventral biceps brachii, according to the recommendations of the International Society of Biomechanics.¹⁹ This reflective marker set-up allowed accurate computation of the wrist's angular position (Figure 1). We did not use an acromion sensor because the scapulo-thoracic joint was not relevant for our aims and has already been studied.¹² Moreover, the participation of the scapulo-thoracic joint was minimized by both the thoracic strap and the reaching distance, which remained within the haptic space.

Data processing

The markers enabled the computation of the following kinematic parameters: (i) MT, (ii) PV, (iii) time of PV (TPV) expressed either as a percentage of MT (TPV %) or in absolute time (ms), (iv) elbow and wrist maximal height. In the grasping task, the wrist angle was computed at the starting position, the PV, and the movement end point. Movement onset and movement end point were defined using a speed threshold of 0.01 m/s. The PV of the wrist marker, determined during the reaching movement, corresponded to the maximal velocity. The MT corresponded to the duration between movement onset and

Table 1 Participant characteristics

Patient	P1	P2	P3	P4
Gender	Male	Female	Male	Male
Age (years)	18	31	24	37
Time post injury (months)	17	33	6	216
ASIA level	C6	C6	C6	C6
Frankel score (A-E)	A	A	B	B
Motor ASIA score (/100)	26	24	26	22
sensitive ASIA score (/112)	50	28	68	68

Abbreviation: ASIA, American Spinal Injury Association.

Figure 1 Description of the experimental set-up for the pointing task (a) and for the grasping tasks (b). Pointing movements were performed following the predetermined order sequence: Right (R), Center (C), R, R, C, R, R, C, C, C, R, C, R, C, R, C, C, R, R, C.

end point. Temporal parameters were expressed as a percentage of MT to obtain the same duration for all movements and to enable comparisons between the two groups.

Statistical analyses

Means and standard deviations were calculated for each participant for each movement. Non-parametric statistical analyses were performed using Mann-Whitney *U*-tests. The threshold for significance was set at 0.05.

RESULTS

In the pointing task, the participants with C6 quadriplegia had longer MTs and lower PVs than the control group, but these differences were not statistically significant. Wrist and elbow maximal heights were not different between the two groups (Table 2). For the participants with C6 quadriplegia, elbow height during right target pointing was significantly lower than during central target pointing. The normalized velocity profiles for both the participants with C6 quadriplegia and the controls followed a bell-shape distribution, and the TPV expressed as a percentage of MT did not differ between the two groups in both central and right target pointing (Figure 2). Finally, there were no significant differences between the two groups for pointing accuracy in the X and Y axes for the central target (mean diff 1.0 mm; 95% CI -6.5 to 8.6 and -3.0 mm; 95% CI -5.1 to -0.9, respectively) or the right target (-2.8 mm; 95% CI -11.0 to 5.3-43.3 to 67.7 and 4.2 mm; 95% CI -16.1 to 24.6, respectively).

In the grasping task, the participants with C6 quadriplegia showed significantly longer MTs than controls for the whole hand grip (mean diff 1123.4 ms; 95% CI 277.2-1969.5) and lateral grip tasks (mean diff 890.8 ms; 95% CI 672.5-1109.1), and both tasks were associated with lower PVs than controls. Interestingly, the absolute TPV was not significantly different between the participants with C6 quadriplegia and controls for either the whole hand grip or lateral grip tasks (Table 3).

The wrist angular position was significantly different between the two groups at the starting point, TPV and movement end point in both prehension tasks. In the whole hand grip task, the participants with C6 quadriplegia started with the wrist in a neutral position whereas the control group started the movement with the wrist extended (mean diff 64.4°; 95% CI 55.4-73.3). At the TPV, the participants with C6 quadriplegia exhibited wrist flexion whereas the wrist extension in the control group was still present (mean diff 92.3°; 95% CI 62.0-122.6). At movement end point, both groups showed wrist extension, and the wrist was more extended in the participants with C6 quadriplegia than in the controls (mean diff 59.3°; 95% CI 29.7-88.9; Figures 3 and 4). In the lateral grip task, a similar pattern was observed for wrist position, with more wrist flexion in the participants with C6 quadriplegia than controls at movement onset (mean diff 62.5°; 95% CI 56.6-68.5) and at the TPV (mean diff 76.4°; 95% CI 54.9-97.9) but more wrist extension than control at movement endpoint (mean diff 27.4°; 95% CI 6.8-48.1). In the whole hand

Table 2 Temporal and kinematic parameters (mean and s.d.) of a pointing movement in four participants with C6 quadriplegia and four matched control participants

	Central target				Right target			
	Controls	C6 patients	MWW test		Controls	C6 patients	MWW test	
			Z	P			Z	P
Movement time (ms)	438.5 (136.8)	659.8 (198.4)	-1.73	0.08	469.2 (138.3)	667.5 (235.1)	1.44	0.25
Peak of velocity (mm/s)	944.2 (219.4)	657.1 (173.9)	1.44	0.15	1145.2 (249.8)	782.1 (190.6)	-0.86	0.15
Time of peak velocity ^a	38.7 (1.9)	40.3 (8.4)	-0.87	0.39	40.7 (2.9)	43.3 (5.4)	0.43	0.39
Elbow height (mm)	36.5 (19.5)	40.1 (20.2)	0.14	0.89	34.9 (6.7)	24.3 (17.8)	1.01	0.67
Wrist height (mm)	32.7 (10.2)	38.1 (13.5)	-0.14	0.89	34 (0.4)	35 (10.4)	-1.16	0.31

Abbreviation: MWW, Mann-Whitney *U*-test.

^aTime of PV has been expressed in percentage of movement time.

Figure 2 Velocity profile (mean and s.d.) normalized with 200 samples for the C6 quadriplegic (black) and control (gray) groups during pointing toward a central (a) and a right target (b). All movements performed either by participants with C6 quadriplegia or by control participants were shorter than 200 samples in the pointing task. Consequently, samples have been added during normalization using the spline interpolation algorithm.

Table 3 Temporal and kinematic parameters (mean and s.d.) of two grasping movements in four participants with C6 quadriplegia and four matched control participants

	Whole hand grasp				Lateral grasp			
	Controls	C6 patients	MWW test		Controls	C6 patients	MWW test	
			Z	P			Z	P
MT (ms)	771.4 (86.7)	1894.8 (596.5)	-2.31	0.02	748.0 (122.2)	1638.8 (130)	-2.31	0.02
PV (mm/s)	799.5 (77.4)	706.3 (126.1)	1.16	0.25	686.3 (78.8)	672.2 (91.6)	0.29	0.77
Absolute time of peak velocity (ms)	346.2 (81.0)	431.9 (103.6)	-1.44	0.15	344.9 (79.8)	414.7 (110.9)	-0.87	0.39
Wrist angle at starting point (°)	20.8 (7.3)	4.9 (5.3)	2.31	0.02	20.1 (6.1)	7.4 (4.8)	2.02	0.04
Wrist angle at PV (°)	12.9 (9.2)	-15.2 (11.9)	2.31	0.02	17.9 (11.4)	-4.3 (10.9)	2.02	0.04
Wrist angle at movement end point (°)	3.9 (12.5)	26.8 (9.4)	-2.02	0.04	17.3 (6.4)	45.3 (10.3)	-2.31	0.02
Max wrist height (mm)	78.9 (12.1)	122.8 (33.8)	-2.02	0.04	72.2 (20)	114.6 (37.6)	-1.44	0.15
Max wrist extension (°)	90.7 (10.1)	112.2 (11.1)	-1.15	0.25	79.7 (8.4)	105.0 (5.5)	-2.31	0.02
Time to max wrist extension*	78.2 (5.4)	40.4 (14.8)	-2.02	0.04	50.6 (26.1)	36.8 (14)	1.15	0.25

Abbreviation: MWW, Mann-Whitney U-test.

*Time to maximal wrist extension has been expressed in percentage of movement time.

Figure 3 Wrist angular position (mean and s.d.) in the sagittal plane in participants with C6 quadriplegia (black) and control participants (gray) performing a whole hand grasp, shown for the starting point (A), the point of peak of velocity (B), and the movement end point (C).

grip task, the participants with C6 quadriplegia had significantly greater wrist height values than the control participants (mean diff 44.0°; 95% CI 8.1–96.1). In the participants with C6 quadriplegia there was significantly more wrist extension in the lateral grip task compared with the whole hand grip task ($112.2^{\circ} \pm 11.1^{\circ}$ vs $105.5^{\circ} \pm 5.5^{\circ}$).

DISCUSSION

In this study, a detailed kinematic analysis of the tenodesis grasp was performed in four participants with C6 quadriplegia and compared with four age-matched healthy control participants in a pointing task and two daily life prehension tasks involving two distinct grips (whole hand grip and lateral grip).

In the pointing task, longer MTs and lower PVs were found in the C6 quadriplegics, in agreement with previous studies.^{10–12} These kinematics modifications are the consequence of a muscle strength deficit caused by the cervical spinal cord injury. The increased elbow height can be explained by compensatory mechanisms of the scapulothoracic joint.¹² Interestingly, although the movement was slower, pointing accuracy was similar in both groups, suggesting that proximal motor control following cervical spinal cord injury is efficient. Lack of temporal constraints in the pointing task allowed participants with C6 quadriplegia to point with an accuracy similar to that of control participants by performing a slower movement.

In the grasping tasks, control participants performed prehension grips using their fingers and small wrist movements. Similar results have been previously reported.^{6,7} Unlike controls, participants with C6 quadriplegia showed enhanced wrist extension during the prehension grips. In participants with C6 quadriplegia the initial wrist position was neutral, showing a lack of active contraction of wrist extensor muscles. Then, during the reaching phase, the wrist was flexed to ensure a maximal aperture of the fingers enabling a maximal wrapping of the fingers around the object. Finally at movement end point, wrist extension permitted closure of the fingers (whole hand grip) or adduction of the thumb against the lateral face of the forefinger (lateral grip). In brief, in participants with C6 quadriplegia performing a prehension movement, wrist movements are essential for the tenodesis grasp: the wrist is initially flexed to open the fingers and it is then extended to produce finger closure.^{11,18}

The angular position of the wrist in the sagittal plane could be considered as a kinematic parameter that reflects the grasping component of reach-to-grasp movements in C6 quadriplegics. This parameter was assessed in a previous study in 11 right-handed participants with C6 quadriplegia by Hoffman and colleagues using a cone prehension grasping task. These authors showed that participants with C6 quadriplegia produced a lot of wrist extension during grasping to passively close the fingers around the object. Our findings

Figure 4 Wrist angular position profile (mean and s.d.) in the sagittal plane (a) and wrist velocity profile (mean and s.d.) (b), normalized with 200 samples in the participants with C6 quadriplegia (black) and control participants (gray) performing a whole hand grasp (left panel) or a lateral grasp (right panel). All movements performed either by controls or by participants with C6 quadriplegia were shorter than 200 samples in the grasping tasks. Consequently, samples have been added during normalization using the spline interpolation algorithm.

show that a lot of wrist extension is also present during whole hand and lateral grips.

The degree of wrist extension might therefore provide some information about the final adjustments that are necessary to secure the tenodesis grasp. We observed significantly more wrist extension during the grasping phase of the lateral grip than the whole hand grip. From a biomechanical perspective, a lot of wrist extension could serve to substantially shorten the flexor pollicis longus tendon, flexor digitorum profundus and superficialis tendons to ensure the security of the grip. However, for the lateral grip the tendons need to shorten more because the object being grasped is smaller. In sum, participants with C6 quadriplegia use different degrees of wrist extension to ensure that tendons are short enough to optimize the security of the grip.

Participants with C6 quadriplegia performed slower movements as compared with control participants, and the TPV in absolute time did not differ between the two groups, suggesting that the reaching phase was prolonged for the C6 quadriplegics. Longer reaching times and wrist flexion during reaching but extension during grasping suggest that the prehension movement was performed in two successive stages in C6 quadriplegics. This finding confirms previous results reported by Hoffman *et al.*¹⁷ who showed a temporal dissociation between the reaching and the grasping components in C6 quadriplegics. Our results suggest that this sequential planning of reaching and grasping is also present in a whole hand grip and a lateral grip task.

CONCLUSION

We report that participants with C6 quadriplegia at a chronic stage (median 25 months after injury) performed tenodesis grasp using a characteristic wrist angular movement in the sagittal plane. The tenodesis grasp is a new higher order program controlling prehension movements, which necessitates a prolonged reaching phase and a final adjustment of the grip. These two features of tenodesis grasp kinematics suggest sequential planning of the reaching and grasping phases. These data are important for prehension rehabilitation in patients with quadriplegia.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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