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Original Article

How do C6/C7 tetraplegic patients grasp balls of different sizes and weights? Impact of surgical musculo-tendinous transfers

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Study design: Prospective control cohort study.
Objectives: To develop a new test to analyse qualitatively grasping strategies in C6/C7 tetraplegic patients, and to quantify the effect of musculo-tendinous transfers.
Setting: France.
Methods: Twelve C6/C7 tetraplegic adults (17 arms; 31.3±7.9 years) and 17 healthy subjects (30.9±9.4 years) completed the study. We assessed participants' ability to grasp, move and release standardized balls of variable sizes and weights.
Outcome measures: Failures, movement duration (MD), grip patterns, forearm orientation during transport.
Results: In patients as well as in controls, the number of digits involved in prehension increased proportionally to the size and weight of the ball. C6 non-operated tetraplegic patients failed 38.2% of the tasks. They frequently used supine transport (51.4% of successful tasks). MD was longer, with a large distribution of values. The presence of active elbow extension poorly influenced the amount of failure nor grip configuration, but significantly reduced MD and supine transport (34%). Patients who were evaluated after hand surgery showed a trend towards improved MD and more frequent completion (failure 30%), especially for middle-sized and middle-weighted balls. Grip patterns were deeply modified, and all transports were made in pronation.
Conclusion: The 'Tetra Ball Test' evidences the characteristics of grasping in tetraplegic patients and those influenced by surgery. It may be useful in understanding effects of surgical procedures. This preliminary study must be completed to evaluate the quantitative responsiveness and reproducibility of this test and to develop instrumented electronic balls to optimise it.
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Keywords: prehension; prehension assessment; tetraplegia; spinal cord injury; tendon transfer surgery

Introduction

Patients with a spinal cord injury at the cervical level resulting in ASIA C6 motor level[1] have minimal loss of strength in shoulder muscles, elbow flexors and wrist extensors. They experience paralysis of the Triceps Brachii (TB), the finger flexors, the finger extensors and the intrinsic muscles of the hand. However, despite this extensive impairment, these patients are able to learn new movement strategies and to perform functional prehension movements after a long period of rehabilitation.[2,3] These new strategies have been poorly investigated.[4] On the one hand, as it is usually admitted in clinical practice, the patients might extend their elbow by using the dynamical interaction coupling produced by external rotation and abduction in the shoulder complex.[5] On the other hand, active extension of the wrist leads to passive finger flexion, and passive flexion of the wrist owing to gravity leads to passive finger extension.[3–7] These two compensation strategies allow C6 tetraplegic patients to grasp and release middle-sized light objects[3] despite severe paralysis of arm musculature.

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In some cases, tendon transfers of intact arm or hand muscles are carried out through reconstructive surgery to restore lost function.[8–10] To compensate the paralysis of the triceps, a transfer of the distal anatomical insertion of either the deltoid or the Biceps Brachii onto the triceps tendon is now currently proposed. To restore active grasp and key grip, several surgical procedures are available by transferring redundant non-paralysed muscles of the forearm on fingers flexors or extensors: usual motors of active transfers are Brachio Radialis and Extensor Carpi Radialis Longus. These surgical procedures are followed by an intensive period of rehabilitation and lead to a recognised functional benefit in daily life.[11–13]

A test is needed to investigate and evaluate the grasping strategies in tetraplegic patients to determine (1) the exact way C6 tetraplegic persons, without any surgical procedure, can grasp and release standard objects and (2) the way functional surgery of the elbow or of the hand improves these capacities of prehension. Although many descriptions of tests designed to evaluate upper extremity function are available, most of the existing tests are inappropriate for this application and patient population.[10,14] The tests aiming to evaluate the impairment of the hand are limited to the measurement of strength and joint motion.[11,15–17] Most of the tests for the evaluation of the motor capacity of the hand[7,10,11,18–21] are only performance tests and give no details on hand grip configurations during prehension. More global functional evaluations assess many functions in addition to hand performance[2,22,23] and are sensitive to additional variables (eg motivation, choice of the tasks or choice of the objects). The strengths and limitations of the methods proposed to evaluate hand function in tetraplegic persons before and after surgery is a topic of interest, considering metrological and conceptual difficulties.[10,24]

Therefore, the aim of this study was to develop an objective, quantitative and qualitative test to assess basic hand performance in the context of manipulating objects. This test was designed to be sensitive to the various neuromotor impairments in tetraplegic patients (including proximal muscle strength and trunk balance) but insensitive to the confounding factors inherent in activities of daily living (ADL). Our 'Tetra Ball Test' drew its inspiration from the method described by Cesari and Newell,[25] who examined, in a population of healthy subjects, the preferred human grip configurations used to move cubes that systematically varied in length, weight and density to a new location.

Materials and methods

Participants

Seventeen healthy subjects and 12 tetraplegic patients were tested. All volunteered after having been informed of the experimental aim of the study, which had received the approval of the local Ethics Committee.

Patients receiving follow-up at the Physical Medicine and Rehabilitation Department of our institution were recruited to the study. Only ASIA C6 or C7 tetraplegic patients according to the American Spinal Injury Association scale[1] were eligible, with a minimal time between the onset of the tetraplegia and the inclusion in the study of 6 months. They had to be able to grasp a medium-sized light ball ('standard ball': 3 cm of diameter, 5 g), owing to their active extension of the wrist.

Non-inclusion criteria were as follows: neurological level under C6 or above C7, joint contractures or spasticity leading to inability to grasp the 'standard ball'.

The 12 tetraplegic patients involved in this study had their right or their left arm studied, according to various practical contingencies. At least 8 months before the study, all had sustained a traumatic spinal cord injury at the C6 or C7 level leading to a motor complete tetraplegia below the injured level. Four patients were examined on both sides. There were a total of 17 experimental sessions for tetraplegic patients. A brief description of the 12 patients (17 arms) is given in Table 1.

At each session, a clinical testing of the muscles of the arm was performed,[16] and the patient was assigned to one of the three following groups according to the score of the TB and to the patient's progress in the surgical programme.

- The first group ('group A': eight arms) consisted of C6 tetraplegic patients who were unable to extend the elbow against gravity (TB score $<3/5$). All patients of this group performed prehension by passive tenodesis of the finger flexors when the wrist was extended.
- The second group ('group B': four arms) consisted of patients who were able to perform an elbow extension against gravity. Three patients of this group had undergone surgery (tendon transfer to restore elbow extension). The muscle transferred onto the TB was either the posterior deltoid (one patient) or the Biceps Brachii (two patients). One more patient (Fre), who was ASIA C7 and had no weakness of the TB, was included in this second group.
- The third group ('group C': five arms) consisted of patients who were tested after surgical restoration of prehension. Four of them had a C6 level according to ASIA classification. They underwent a first intervention to restore elbow extension (two of them sustained a transfer of the Biceps Brachii and the two others a transfer of the posterior deltoid). After at least 6 months, these patients had two interventions to restore finger flexion and extension (see below). The fifth patient, who had a C7 level, had only two interventions at the hand.

Hand surgery consisted of a two-staged programme to successively restore 'hand opening', followed, 3 or 4 months later, by 'hand closure'.[26] Reinforcement of 'hand opening' consisted of passive procedures for two arms (tenodesis of the Extensor Digitorum

Table 1 Main clinical data of tetraplegic patients

Arm	*Patient*	*Side*	*Gender*	*Age*	*Post-injury delay*	*ASIA level*	*GIENS group*	*Elbow surgery*	*Hand surgery*	*Group*
2	Daa	R	M	27	5.5 months	C6	4	—	—	A
3	Elb L	L	M	24	4.5 years	C6	2	—	—	A
4	Elb R	R	M	24	4.5 years	C6	2	—	—	A
12	Jub	R	F	17	8 months	C6	3	—	—	A
13	Pai	R	F	36	15 months	C6	2	—	—	A
16	Bru R	R	F	23	3 years	C6	4	—	—	A
7	Fri	R	M	51	26 years	C6	2	BB/TB bad result	—	A
10	Pic	L	M	36	4 years	C6	4	D/TB bad result	—	A
5	Eli	L	M	34	2.5 years	C6	2	BB/TB	—	B
6	Ber R1	R	M	32	2.5 years	C6	2	BB/TB	—	B
17	Bru L	L	F	23	3 years	C6	3	D/TB	—	B
11	Fre	R	M	43	21 years	C7	5	—	—	B
1	Mar L	L	M	33	3.5 years	C6	4	D/TB	Yes	C
9	Mar R	R	M	34	4 years	C6	3	D/TB	Yes	C
14	Ber L	L	M	33	4 years	C6	2	BB/TB	Yes	C
15	Ber R2	R	M	33	4 years	C6	2	BB/TB	Yes	C
8	Dru	R	M	30	3 years	C7	5	—	Yes	C

Twelve patients completed the study, representing 17 arms (groups 2–5 in the international classification)[26]
L, left; R, right; GIENS, group appurtenance according to the Second International Conference on Surgical Rehabilitation of the Upper Limb in Tetraplegia;[26] D, posterior deltoid; TB, Triceps Brachii; BB, Biceps Brachii

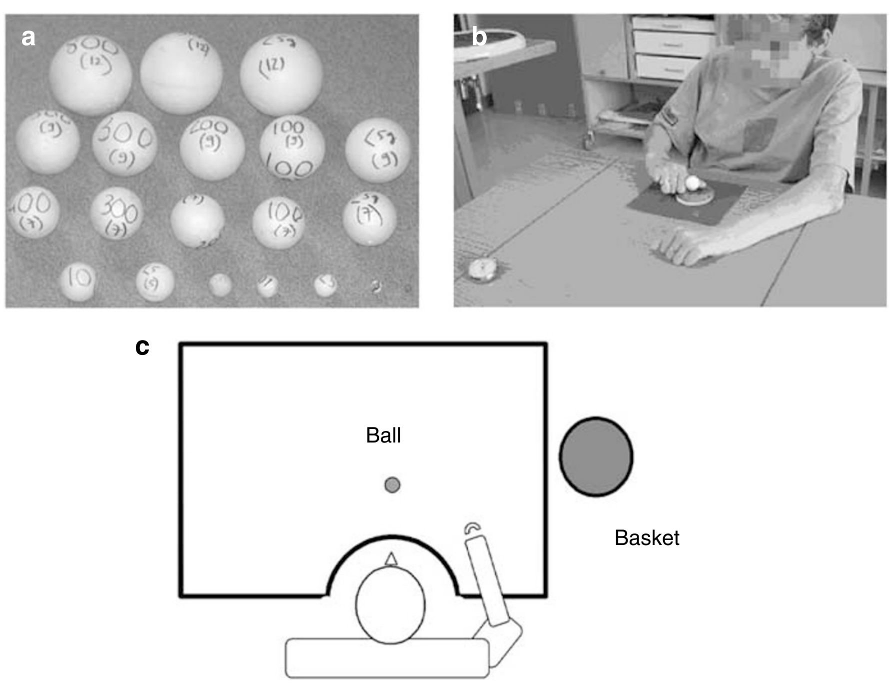

Figure 1 (**a**) The 20 non-slippery balls ranging in order of size and weight. (**b**) Experimental set-up and installation of the patients. (**c**) Drawing of the experimental set-up: the subject seats in front of the table. The ball is placed on the table on its initial position, in front of the subject. The final basket is drawn on the right

Communis (EDC) and the Extensor Pollicis Longus (EPL) to the Extensor Retinaculum of the wrist), active transfer for two arms (transfer of the Brachio Radialis to the EDC and the EPL) and side-to-side suture of the EDC tendon of the index finger to the rest of the EDC tendons in one case. Restoration of active finger flexion consisted of transfer of the Extensor Carpi Radialis Longus (ECRL) to the Flexor Digitorum Profundis (FDP) in three cases and in transfer of the BR to the FDP in two cases. All patients underwent passive direct lassos as described by Zancolli[27] to prevent claw deformity relative to muscular imbalance between intrinsic and extrinsic muscles of the fingers.

Table 2 Distribution of the 20 balls (from B1 to B20) according to their weight (lines) and diameter (columns)

	0.5 cm	*1 cm*	*3 cm*	*5 cm*	*7 cm*	*9 cm*	*12 cm*
<5 g	B1	B2	B3	B5	B8	B13	B18
100 g			B4	B6	B9	B14	
200 g				B7	B10	B15	
300 g					B11	B16	B19
400 g					B12		
500 g						B17	
800 g							B20

Seventeen healthy subjects participated in the study as control subjects. None of them had any past history of neurological or orthopaedic disorders. All of them were right-handed and had their right arm studied.

Experimental set-up

The table used for this experiment was of variable height and was adjusted at the level of the xyphoid process with respect to the individual participant's height.

Twenty different balls have been developed for qualitative and quantitative assessment of prehension tasks performed with one of the hand (Figure 1a). The choice of balls as standard objects avoided difficulties with orientation of the hand in those patients who lacked control of active pronation of their forearm. The balls were custom made from commercially available polystyrene spheres loaded with lead shots at their centre. The surface texture of the balls was non-slippery and was the same throughout the 20 balls, except for the two smallest balls, which were marbles. The repartition of the size (from 0.5 to 12 cm) and the weight (from a few grams to 800 g) of the balls was carefully chosen with regard to the work by Cesari and Newell,[25] to provide graded indexes of difficulty within a reasonable range for tetraplegic patients. According to these authors, the difficulty of the prehension increases with the size and the weight of the ball. In our experimental set-up, the difficulty of prehension is indicated by the ball's number in the series, as described in Table 2.

Procedure

For each participant, we initially collected standard anthropometric measures of hand size: hand width (HW) and hand length (HL).

The participant's task was to complete a series of trials in which a ball placed on the table had to be grasped with one hand and moved from its initial position to a new final position (see Figure 1b and c). The initial position was on the body midline, in front of the subject. Its distance from the table edge was equal to the length of the forearm plus the hand and was measured for each participant. The final resting target position of the balls was also body-scaled, and it consisted of a circular basket disposed laterally at the level of each participant's shoulder, at a distance equal to the length of the entire arm.

Subjects began each trial with the elbow and wrist resting on the table in front of them, just near the initial position of the object to be grasped, with the hand in a semi-pronated position. The participants were instructed that after the starting signal, they were to 'grasp and displace the ball to the new final position'. They were instructed to perform the movement at 'natural speed' and not to try to do it as fast as possible. The presentation order of the 20 balls was the same across subjects (from B1 to B20). For each ball, the participants first performed a practice trial and then performed three experimental trials. Thus, the total number of grasping trials performed by each subject in this experiment was 60. Depending on the weakness of the subjects, a few minutes of rest was allowed if needed between trials.

Grasp patterns were not specified and patients were allowed to manipulate the balls with palmar grasp or lateral grip. All the compensation strategies were permitted (eg supination of the forearm and stabilisation of the trunk with the contra-lateral arm), except bimanual prehension.

Recording and data processing

The total time needed to complete the task (movement duration, MD) was measured with a manual chronometer. One of the investigators gave the starting signal, and the chronometer stopped when the subject dropped the ball in the target basket. Maximum permitted time was 30 s: beyond this cutoff time, the task was considered as failed. The number of failures (NF) was noted for each ball.

The grasping routines that the participants performed were videotaped with a camera placed in front of the participants, for subsequent coding of the grip configurations. The experimenter could then categorize: (1) the number of digits used to grasp the ball (ND: from 2 to 5), (2) the variety of grip chosen by the subject to hold the ball (palmar grip (PG), disto-distal grip (DDG) or proximo-distal grip (PDG)) and (3) the orientation of the forearm when transporting the object from its initial position to the target position (HO: prone or supine).

Statistical analysis

Age and anthropometric characteristics were analysed by analysis of variance (ANOVA) or by the unpaired two-tailed Student's *t*-test.

Grasping routine, forearm orientation, number of failures and MD were compared between subject groups and between testing conditions by means of non-parametric statistical tests, because the variance was not always homogenous. The results in tetraplegic patients were compared between groups of patients and with those in healthy subjects (Mann–Whitney (MW) test). The potential effect of the characteristics of the ball (diameter and weight) was investigated within each subject group by a Kruskal–Wallis (KW) test.

$P<0.05$ was considered to be statistically significant.

Results

Population
Healthy subjects aged from 18 to 48 years (mean 30.9 ± 9.4 years) and tetraplegic patients aged from 17 to 51 years (mean 31.3 ± 7.9 years). There were 11 men among 17 in the control group and nine men in the tetraplegic group (representing 13/17 arms). The mean length of the hand was 18.6 ± 1.51 cm for control subjects and 18.2 ± 0.88 cm for tetraplegic patients. The mean width of the hand was 9 ± 0.44 cm for control subjects and 8.4 ± 0.64 cm for tetraplegic patients. All healthy participants had their right arm examined. For tetraplegic persons, we assessed six left arms and 11 right arms.

The two populations were therefore considered as comparable, except for differences in gender distribution and side of examination.

Number of failures
When considering all the testing conditions, healthy subjects successfully completed all the tasks. By opposition, group A tetraplegic patients failed 38.2% of the trials (Figure 2). Group B patients with active elbow extension failed 47% of the trials (not significantly different from group A at MW test). Patients from the group C, who were evaluated after hand surgery, showed a trend towards more completion, with a rate of failure of 30% (not significantly different from group A: MW: $P = 0.15$).

The number of failures depended on the ball (Figure 3a–c). The patients usually succeeded with the small and medium light balls, but failed with the large and heavy balls, or with the smallest one. As shown in Figure 3, the probability of success in tetraplegic patients regularly decreased with increasing ball diameter (noted in the grey scale in the legend) and with increasing weight (see the successive symbols with the same grey level). The influence of the ball diameter was statistically significant in groups A and C (KW group A, $P < 0.0001$; KW group C, $P < 0.0001$), as was the influence of its weight (KW group A, $P < 0.0001$; KW group C, $P = 0.004$). The success probability in group B varied significantly with the size (KW, $P < 0.01$) but not with the weight (KW, $P = 0.17$) of the ball.

The differences between the groups of patients were analysed after assembling the results for the medium-sized balls (3–7 cm of diameter). The probability of success for these medium-sized balls significantly differed between groups (KW, $P = 0.02$). Two-handed comparison using the MW test confirmed that the success rate was significantly higher in group C than in groups A or B ($P < 0.0001$). These patients succeeded in all the trials with the 3–7 cm balls, provided that they were lighter than 300 g (success probability = 1).

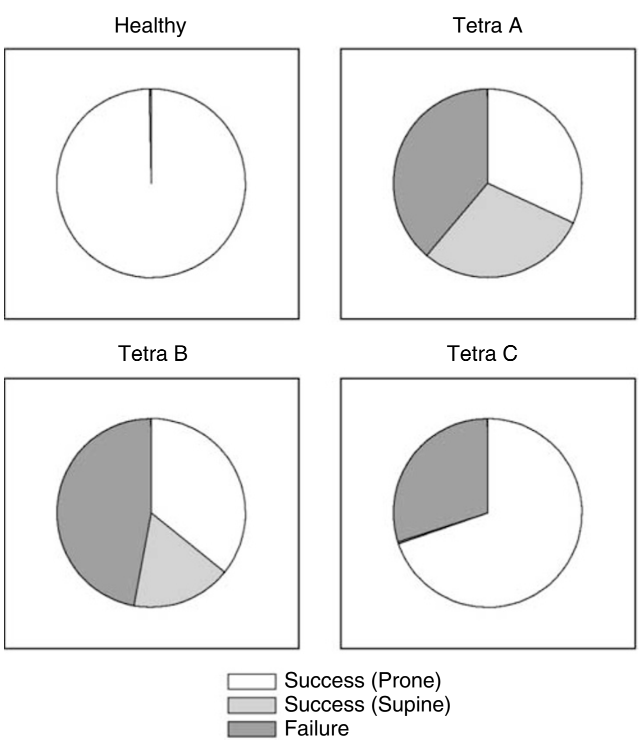

Figure 2 Percentage of failures (in black) and of successful trials with the forearm in supine (grey) or prone (white) orientation for ball transportation in the four populations (healthy subjects and three groups of tetraplegic patients)

Total duration of the movement (MD)
Healthy subjects completed the trial within 2.5 s in 99% of the cases. Tetraplegic patients needed much more time to complete the movements (means 6.5 ± 0.5, 5.8 ± 0.7 and 4.2 ± 0.3 s for the groups A, B and C, respectively), with a much larger variability. The distribution of MD was calculated over three ranges: regular (<2.5 s), medium (2.5–7 s) and long (more than 7 s) (Figure 4). Tetraplegic patients from the group A mostly made medium duration movements (71.43% of the cases), but frequently had to keep on trying to find an appropriate hand configuration to lift the ball during more than 7 s (28.6% of the cases) (Figure 4). The results differed in the other groups, because the patients from group B were more frequently able to make movements faster than 2 s (20.4% of the cases), and patients from group C rarely needed more than 7 s to succeed (11.1% of the cases). χ^2 test showed that the distributions in all the groups of patients were significantly different compared to those in healthy subjects ($P < 0.0001$). There was also a significant difference between both groups B and C compared to group A ($P < 0.001$), but not between groups B and C.

The characteristics of the balls were of poor influence on MD in the three groups of tetraplegic patients.

Hand and fingers configuration
Number of fingers involved in grip Both the size and the weight of the ball influenced the number of digits used for prehension (Figure 5, symbols with different grey

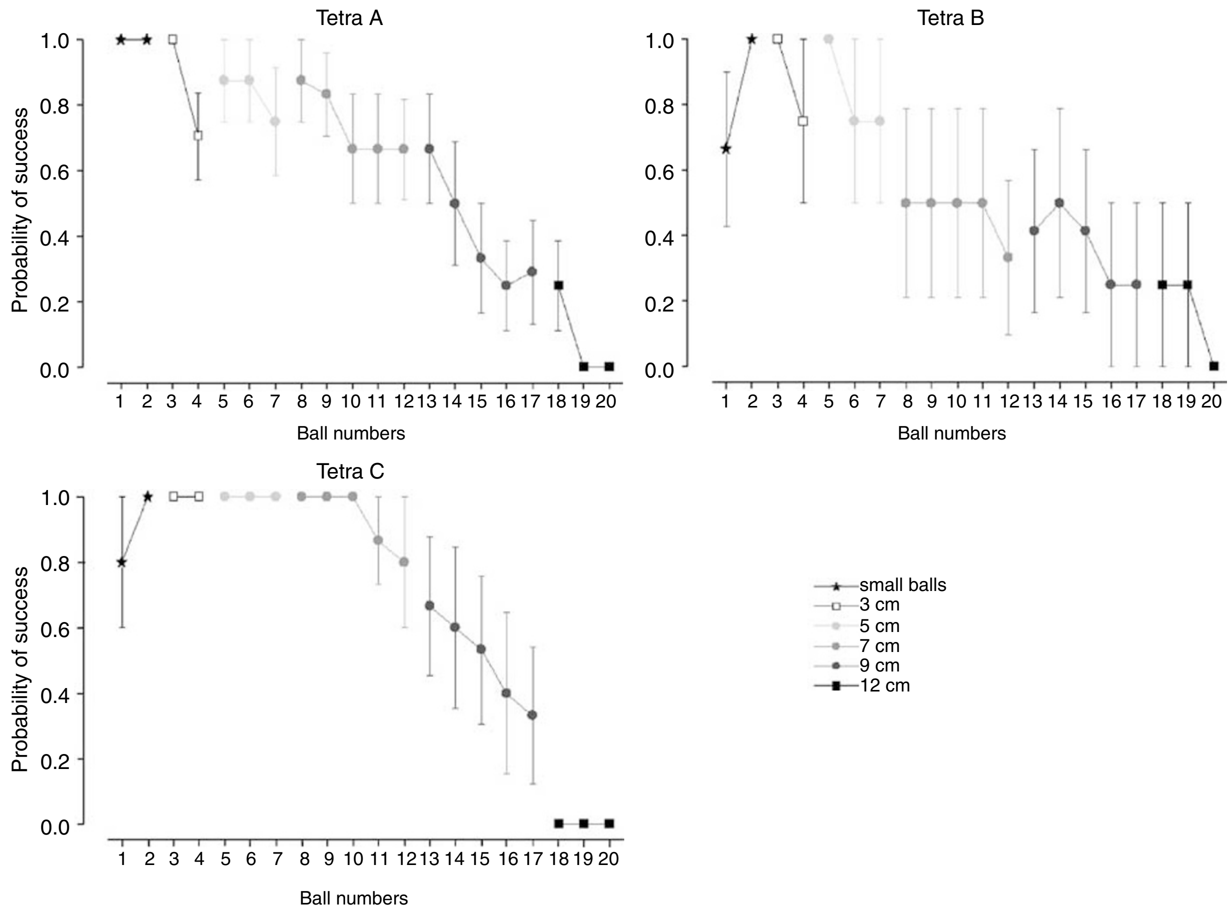

Figure 3 Probability of success as a function of ball number (see Table 2) for the three groups of tetraplegic patients. The ball diameter is indicated by the symbol shape and grey scale. The balls have increasing weights

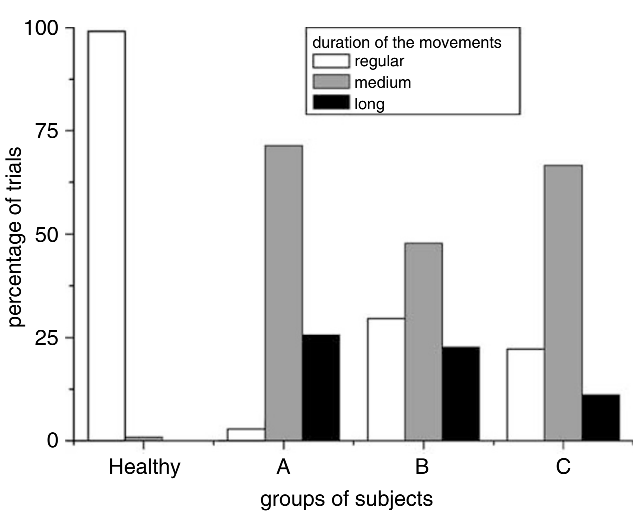

Figure 4 Distribution of MDs calculated over three ranges: regular (<2.5 s), medium (2.5–7 s), long (more than 7 s), in healthy subjects and tetraplegic patients

scale). Healthy subjects took the smallest balls with two fingers and regularly increased the number of fingers, to take the largest ball with all five fingers (KW, $P<0.0001$). The mean number of fingers used to take the ball was sensitive to the weight of the ball, as shown by the regular increase in the number of fingers involved to take heavier balls (see the successive symbols with the same grey level; KW, $P<0.0001$). Similar results were observed in group A (KW, $P<0.0001$) and group B tetraplegic patients (KW, $P=0.0003$ for ball size and $P<0.05$ for ball weight). The results were radically different in the tetraplegic patients who had sustained hand surgery (group C). The size of the ball significantly influenced the number of fingers (KW, $P=0.003$), but the regular increase in the number of fingers according to the graded difficulty of the ball observed in healthy subjects was replaced by an obvious two-level grip configuration. Group C tetraplegic patients used either a two-digit prehension for small or medium-sized objects ($\leqslant$5 cm of diameter, depending on the subject) or three fingers for most of the remaining balls. The weight of the ball did not significantly influence success (KW, $P=0.06$).

Grip pattern Healthy subjects preferred DDGs between the tips of the long fingers and of the thumb for the smallest balls (50% of the tasks). DPGs between

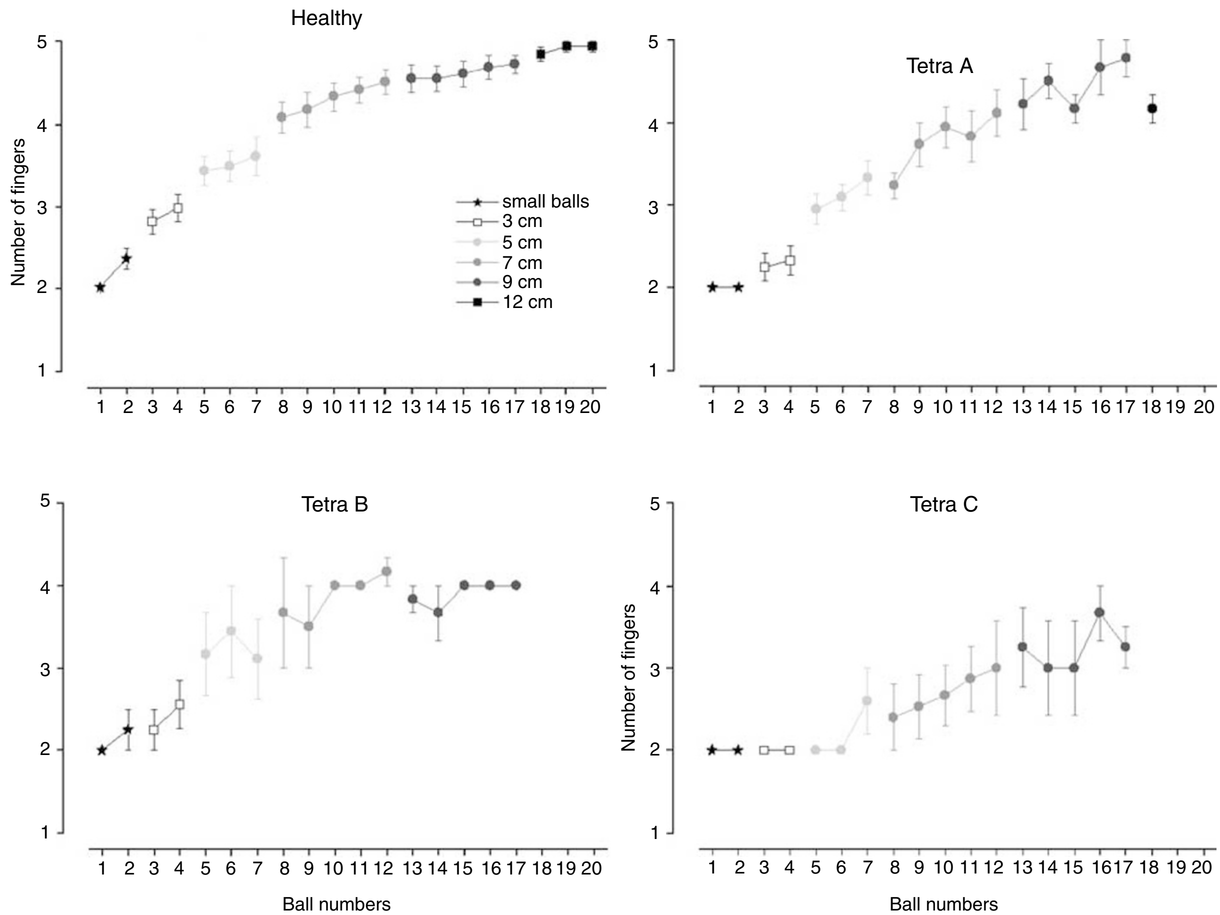

Figure 5 Scaling of the number of digits used to grasp the ball as a function of ball number (see Table 2) for healthy subjects and the three groups of tetraplegic patients. Same legend as in Figure 3

the tip of the thumb and the palmar or lateral part of the second phalanx of other digits were used for the largest balls and represented 49% of the total amount of testing sessions. PGs were an exception.

For tetraplegic patients from groups A and B, DPGs represented 80% of the chosen grips, usually between the thumb and the lateral face of the second phalanx of the forefinger, whereas DDGs represented only 19%. Like in control subjects, palmar grasps were an exception. This result changed after surgery of the hand: DPGs continued to be the favourite way of prehension (75% of the balls), but palmar grasps reached 19% of total.

Forearm orientation during transport of the ball
Healthy subjects always orientated the forearm in pronation to translate objects from their initial to their final position. C6 non-operated patients (group A) used supine transports in 51.4% of successfully performed tasks (representing 29.2% of the total tasks, see Figure 2). Tetraplegic patients with active elbow extension (group B) showed only 34.0% of supine transports (representing 17.1% of the total tasks), whereas subjects who had undergone surgery of the hand (group C) showed $<1\%$ of supine transports (see Figure 2).

The amount of supine transports depended on the weight of the ball in the two groups of tetraplegic patients who had not undergone a surgical procedure at the hand (KW group A, $P<0.0001$; KW group B, $P=0.04$). The size of the ball did not influence the type of transport, as shown by KW test: $P=0.09$ for group A and $P=0.6$ for group B.

Discussion

Comparison of the results in the different populations
The use of a set of balls of increasing sizes and weights allowed a qualitative and quantitative description of the prehension strategies allowing discrimination between healthy subjects and the different groups of tetraplegic patients.

Healthy subjects The results obtained in healthy subjects are consistent with the initial description by Cesari and Newell.[25] The prehension gestures directed at all the balls were executed easily and smoothly so that the task was usually completed within 2 s, with a transport always executed in pronation. According to Cesari and Newell,[25] the number of fingers used for grasping is related to the size and, to a lesser degree, to the weight of the ball. The regular increase in the number of fingers with the rank of the ball shows that our empirical selection of sizes and weights offers a pertinent set of graded difficulties.

'Automatic prehension' in C6 tetraplegic patients Automatic prehension ensures a capacity for prehension in C6 and C7 tetraplegic patients.[2,3] However, this capacity is quite relative and limited, as shown by the results obtained in C6 tetraplegic patients (group A). They showed a high rate of failures, especially for small and large objects (under 1 and over 5 cm of diameter) and for heavy ones (over 200 g). Even when the prehension was possible, it was more difficult than in healthy subjects, as shown by its longer and irregular duration.

In contrast, we observed the counterintuitive phenomenon that the hand configuration is not so different from that used in healthy subjects. In particular, the number of fingers for grasping was graded with the rank of the ball, and the finger configuration was similar, although less frequently DDG. This is consistent with the proposition by Cesari and Newel that the hand configuration for grasping is mainly dependent on the relative proportions of the hand and the object. In addition, we demonstrate here that the muscular strength of the fingers little influences the hand configuration.

The transport of the ball was frequently executed with the forearm in supine position. Indeed, the rotation of the forearm may generate forces contributing to lift the ball, and the hand orientation 'palm above' increases grasp stability when the object is wedged into the hollow of the hand.[28] To our knowledge, the importance of this phenomenon (more than half of the successful tasks in C6 patients) had never been quantified previously.

The transport of the ball towards the reception basket imposed an elbow extension, which was easily executed by the patients. This is consistent with previous studies showing that the kinematics of the hand during reaching movements in C6 tetraplegic patients are surprisingly similar to those of control subjects.[4,5,29] These results indicate that the shoulder musculature plays an important role for generating elbow extension when there is no voluntary active elbow extension.

Importance and function of an active elbow extensor The rate of failures did not vary with the presence of voluntary contraction of the triceps muscle (comparison of groups A and B tetraplegic patients). However, the presence of an active elbow extensor seems to facilitate the execution of the prehension movements, which are executed faster and more frequently with the forearm in pronation. These results corroborate clinical observations of the functional benefits of surgical restoration of active elbow extension by musculo-tendinous transfer.[8,13,24,30]

Current hypotheses concerning the benefit of the presence of an active elbow extensor include the ability to maintain a stable arm posture, especially when the hand is raised above the shoulder level, as is the case in the present task,[31] the ability to interact with a variety of external objects and forces,[32] or the ability to propulse a manual wheelchair. In addition, our results suggest that the presence of a non-paralysed triceps, or of a surgically transferred muscle, facilitates prehension, probably by stabilisation of the elbow during the transport of the objects.[33]

Results of hand surgery Our results confirm that the performance of prehension is largely enhanced by hand surgery in C6 and C7 patients (comparison of group C to groups A and B tetraplegic patients). These functional benefits have been largely demonstrated with different assessment methods, varying from dynamometry to functional evaluation in activities of daily life.[8,10,11,13,30,34] Here, we further analyse the mechanism of this improvement.

The global rate of failures decrease from 39% before surgery of the hand to 30%, with a marked statistical improvement for middle-sized and middle-weight balls. The improvement of the capacity for prehension is also documented by the decrease in MD and the disappearance of supine transports. These observations were empirically reported but, to our knowledge, had never been previously measured.

The results in group C patients confirm that the size and the weight of the object influence the hand configuration for grasping. However, this influence is completely different than that observed in healthy subjects, as well as in patients before surgery. The graded increase in the number of fingers with the index of difficulty of the ball is replaced by a twofold choice between a 'key grip' or a 'palmar grasp'. The key grip involving two fingers is not only used for the smallest balls but also unto the 5 cm diameter balls. For larger balls, the patients used another grip configuration, with 3–4 fingers, depending on the patient, and a palmar grasp. This demonstrates that the surgery induces quite efficient prehension movements but drastically modifies the functional properties of the hand and fingers for grasping. The patients have to choose between the two forceful grip configurations intentionally produced by the surgeon instead of relying on the usual functional anatomy of the hand.

Situation of the 'Tetra Ball Test' for assessment of prehension in tetraplegic patients

Evaluation of function Our first purpose, when developing the present test, was to provide a method for the functional evaluation of prehension which could be together simple, usable in clinical practice, and global enough to integrate the different components of prehension (reaching, grasping and transport of the object). This method is complementary of the measures of the functional outcomes in daily life and of more analytical evaluations of the various neuromotor impairments contributing to the disability. Detailed functional assessments are qualitative, time-consuming, sensitive to many psychological and social variables and often provide limited insight into the mechanisms limiting functional performance.[10,35] Beyond the usual clinical examination, hand function is particularly complex to define, owing to the many degrees of freedom of the hand which afford the wide range and the rich adaptability of human grip configuration. This difficulty is even greater in tetraplegic patients, who have very variant hand postures for daily life prehension tasks.[6] Hence, we chose to analyse grasping gesture prototypes with balls as standard objects. The use of balls limits the possibility of idiosyncratic compensatory strategies, and the selected sizes and weights represent a variety of objects spanning a large range of difficulties thoroughly described in healthy subjects.[25] We maximised the reliability of our test by choosing a qualitative and quantitative scoring method and by using standardized equipment, procedures and instructions. The results yielded interesting information both on the grasping strategies of the patients and on their ability to integrate grasping into reach and transport to perform a finalised prehension.

This test was sensitive and proved useful to evaluate the result of surgery both at the individual and the group level. However, we have to point out specific difficulties in tetraplegic patients, which impose special care of the examiner during the test. Small changes in the hand, particularly the balance between finger flexor and finger extensor tension, can lead to noticeable changes in performance.[36] In one patient, for example, finger extension in palmar prehension produced an intrinsic minus posture (clawing) when he was not using a splint to prevent hyperextension at the metacarpo-phalangeal joint. In other cases, neurological spasms or fatigue can produce highly variable performances, particularly at the end of the procedure.

Perspectives for the analysis of surgical outcome The 'Tetra Ball Test' may be of precious help in discussions around surgical techniques, because it yields accurate enquiries about the intrinsic characteristics of the objects for which the improvement is important. For example, restoration of hand opening is usually based on passive procedures (such as tenodesis and arthrodesis) for groups 2–4 in the international classification.[37] According to other authors,[8] the Brachio Radialis can be used as transfer to the EDC, even in patients with paralysis of the Flexor Carpi Radialis (FCR) in groups 2–4. The 'Tetra Ball Test', focusing on the results concerning the diameter of the objects patients have to grasp and release, could answer this question about the utility to use Brachio Radialis to enhance hand opening. Until now, the answer remains unclear; none of the tests currently available is being able to provide insights into the precise effect of the surgery.

Another example is the way surgery must take into account the size of the injured metamere below the level of the lesion in tetraplegia. For example, the lower motor neuron integrity of intrinsic muscles of the hand may have a strong influence on the quality of the results after tendon transfer and the probability of claw deformities.[38] Restoration of intrinsic balance of the hand could thus be refined (indications and techniques) if precise results concerning the posture of the hand during the grasp were known.

Generally speaking, the choice of the optimal donor muscle in tetraplegic hand surgery should be based on a thorough understanding of the accurate qualitative and quantitative results as provided by the 'Tetra Ball Test'.

Perspectives with instrumented methods The present study also intended to provide an experimental basis and preliminary data to further analyse the prehension of tetraplegic patients with instrumental methods.

The grasping component of prehension can be studied with optical motion analysis systems with sensors on the tips of the thumb and forefinger.[25,39] These methods demonstrated that adults and young children organise the grip configuration before contact with the object, during the reaching phase of the movement. This suggests that the scaling relations are perceived from visual information before hand contact with the object. To our knowledge, this has never been tested in tetraplegic patients. The question relies on the possible anticipation of the grip type (key grip or palmar grasp) and on the possible anticipation of the number of fingers during reaching. The opposite hypothesis is that the number of fingers is determined after the contact, the hand wrapping itself passively around the ball before the lift.

Hand posture can also be measured by resistive sensors embedded in a glove, measuring the rotations of the various hand and finger joints (Cyber Glove, Virtual Technologies, Palo Alto, CA, USA). Such methods look very promising.[40] However, the functional interpretation of the grasp would require the development of complex direct kinematics models. In addition, the precision of these techniques is quite limited for the joint rotations other than flexion-extension (ab-adduction or opposition). These problems are particularly crucial in tetraplegic subjects, who show very variant postures of the hand during grasping, leading to foreseeable difficulties in the interpretation of data.

In the future, we rather plan to equip the 'Tetra Ball Test' with pressure sensors fixed either on the fingers or on the balls.

Conclusion

This efficient approach of prehension in tetraplegic patients represents a practical clinical tool that may be useful for understanding and quantifying the benefit of rehabilitation procedures, functional surgery or future functional electric stimulation (FES) devices. This preliminary study convinced us of the necessity of a qualitative and quantitative prehension capacities test.

The psychometric rigor of our test needs to be further developed to confirm test–retest reliability and ability to detect changes in hand function following tendon transfers or FES. Improvements in our test are in process to build instrumented electronic balls able to measure grasp forces in different axes, number of digits used, orientation of the hand and MD. Simultaneous kinematic study of the reaching phase of the movements should be possible, to complete the results when necessary.

Conflict of interest

No commercial party having a direct financial interest in the results of the research supporting this article has conferred or will confer a benefit upon the authors or upon any organisation with which the authors are associated. We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

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