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Authors' contributions.—Marieke R. Blom-Smink, Mieke W. van de Sandt-Koenderman and Gerard M. Ribbers contributed to conception and design of the study; Marieke R. Blom-Smink collected the data, and performed the statistical analyses with contributions of Hester F. Lingsma and Majanka H. Heijenbrok-Kal; Marieke R. Blom-Smink, Mieke W. van de Sandt-Koenderman, Hester F. Lingsma, and Majanka H. Heijenbrok-Kal interpreted the data; Mieke W. van de Sandt-Koenderman and Gerard M. Ribbers supervised the study; Marieke R. Blom-Smink wrote the first draft of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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Intensive upper limb therapy including a robotic device after surgically repaired brachial plexus injury: a case study

Adult traumatic brachial plexus injury (BPI) often results in upper limb paresis and causes chronic disability and pain. The gold standard treatment after a brachial plexus roots rupture or avulsion is nerve surgery.[1] Rehabilitation focuses on conservative approaches. The impact of rehabilitation on motor recovery has little been studied. However, evidence from animal models suggests that activity-dependent interventions[2] may enhance axonal regeneration. Over the last decades upper limb rehabilitation robots integrated neurorehabilitation programs to provide intensive training, mainly after stroke.[3]

This paper reports changes in motor outcomes in a young man after traumatic BPI during a comprehensive rehabilitation program that included robotic therapy. The patient, a 25-year-old male, was injured in a motorcycle accident. He sustained a middle-third clavicle fracture associated with a brachial plexus injury. The initial clinical examination showed complete motor deficit of the shoulder and elbow muscles and paresis of the wrist and finger extensors. The patient consulted a specialized surgeon one month later. ES (electrophysiological studies) showed a C5-C6-C7 BPI (Table I) and MRI confirmed complete avulsion of the C5/C6 roots (Figure 1).

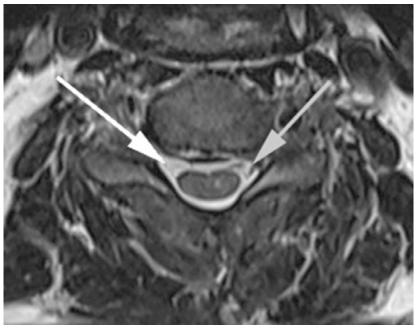

Figure 1.—RMI of the C5 root showing the avulsion with no visible anterior and posterior part of the root (white arrow) compared to contralateral side (grey arrow). The same image is present concerning the C6 root.

Three months later, he underwent a transfer of the nerve of the rhomboid muscle to the suprascapular nerve to reinnervate the rotator cuff[4] and a double transfer of fascicles was performed under electrical stimulation: one motor fascicle harvested from the ulnar nerve rerouted onto the branch of the long head of the triceps brachii and one motor fascicle harvested from the median nerve rerouted onto the nerve of the biceps muscle. Five weeks after the surgery, the patient was admitted into our neurological rehabilitation unit. On admission, he had no neuropathic pain and no visible or palpable contraction at any shoulder muscle or the elbow flexors with only a slight contraction of the triceps brachii. The patient integrated a standard rehabilitation program that was complemented by upper limb robotic training.

Rehabilitation consisted of occupational therapy (OT), physiotherapy with electrical stimulation (ES) and upper limb robot-assisted sessions, each for one hour, five days per week. This single case study was conducted in accordance with the Good Clinical Practice guidelines and local regulatory requirements. OT sessions included strengthening of pronation, supination, wrist extension, finger flexion and extension, as well as prehension tasks. ES sessions involved stimulation of Deltoid and Brachii Biceps muscles using Genesy 3000 rehab Globus®.

Robotic therapy and robot-based kinematic assessment used an end-effector device, the InMotion 2.0 (Interactive Motion Technologies, Inc., Watertown, MA) (Figure 2A). This robot assists shoulder (flexion/extension) and elbow (flexion/extension) movements in the horizontal plane using a performance-based algorithm that adjusts forces to assist or challenge movements

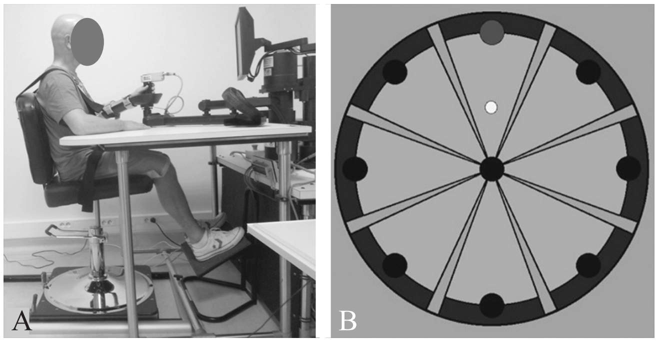

Figure 2.—InMotion 2.0 Arm robotic device; A) patient using the robotic system; B) reaching movement task interface.

TABLE I.—*Electromyography: ulnar and median nerve are preserved. The rhomboid muscle was functional albeit the C5 avulsion. As a matter of fact, the nerve dorsal scapular receives branch C2C3C4.*

	Stimulus	Recording	Nerve conduction (m/s)	Motor potential	Amplitude (ms)	Distal Latency (mV)
Suprascapular nerve	Erb's point (3cm above the clavicle)	Supra and infraspinatus fossa	0	0	0	0
Nerve of the rhomboid		Mid-distance between medial edge of the scapula and spine	Not available	Normal	8	3.4
Axillary nerve		Mid-point between acromion and the tip of the deltoid insertion	0	0	0	0
Median nerve		Mid thenar area	50 m/s	Normal	5	4.2
Ulnar nerve		Mid hypothenar area	54 m/s	Normal	10	2.6
Radial nerve		Lateral part of the bicipital groove	0	Small	1	4.2

TABLE II.—*Clinical motor outcomes: MRC grading score over therapy between 1.3 and 22.3 months after surgery. MRC score is graduate from 0 (no muscle contraction) to 5 (normal power).*

	Test1	Test2	Test3	Test4	Test5	Test6	Test7	Test8	Test9
Delay postsurgery (days)	38	83	111	175	261	342	413	519	668
Delay postsurgery (months)	1.3	2.8	3.7	5.8	8.7	11.4	13.8	17.3	22.3
Lateral deltoid	0	1	2	2	2	2	3	3	3
Biceps brachii	0	1	1	2	2	2	3	3	4
Triceps brachii	2	2	2	2	2	2	3	3	3
Pronator muscles	2	2	3	3	3	3	3	3	3
Supinator muscles	0	2	3	3	3	3	3	3	3

according to motor performance. It provides repetitive goal-directed movement-based therapy with several training modes from active-assisted to resistive. The system is equipped with sensors that record hand displacement in the horizontal plane, from which kinematic parameters are calculated. During the evaluations, the patient performed 80 unassisted center-out point-to-point reaching tasks towards targets set in 8 compass directions (Figure 2B).

Monthly clinical assessments were carried out and when possible robot-based kinematic assessments were also performed. Strength was measured using the medical research council (MRC) grading scale for the deltoid, triceps brachii, biceps brachii, pronator and supinator muscles. The MRC scale grades muscle force between 0 (M0) to 5 (M5).

Kinematic variables were extracted from the robot kinematic assessment; mean movement speed (MMS), peak movement speed (PMS), path error (PE) calculated as the mean deviation from the straight line (m) and active range of motion (AROM), which measures the average distance covered from the center towards the target. A smoothness metric was also calculated (mean speed divided by peak speed).

The patient underwent a total of 18 months of rehabilitation. During the first 3 months, the assist-as-needed algorithm was used and he completed 55 robot-assisted sessions, performing an average of 680 movements per/session. In the subsequent months, the patient carried out 159 sessions (both non-assisted and resistive programs), with an average of 945 movements per/session. No pain was reported by the patient during or after the sessions. MRC grading scores are summarized in Table II. During the rehabilitation period there were significant improvements (Figure 3) for velocity (+77% for MMS, +39% for PMS and +24% for smoothness) and for the control of movement (-73% for PE) contrary to the movement amplitude which did not show significant evolution (+1% for AROM). These changes are also visible on the trajectories of the hand (Figure 4).

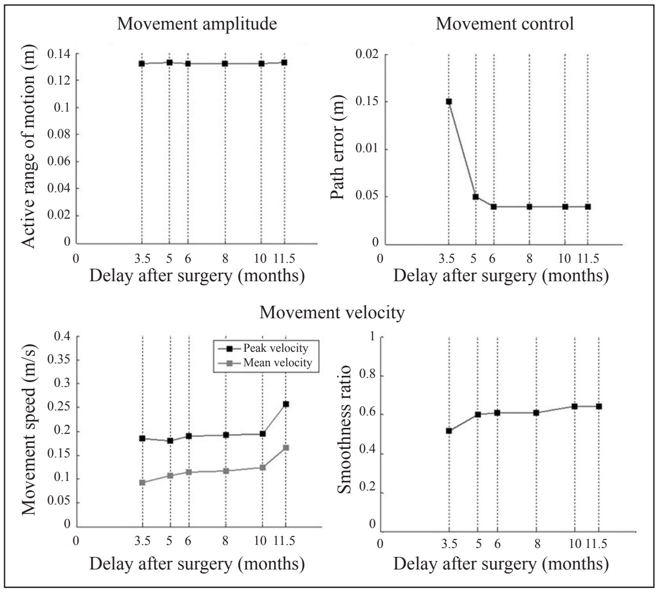

Figure 3.—Evolution over therapy (between 3.5 and 11.5 months after surgery) of kinematic robotic parameters. Active range of motion is the average distance the patient can cover from the center towards the target; movement speed shows in grey the mean velocity and in black the peak velocity; smoothness ratio is the mean speed divided by peak speed and path error is a measure of movement accuracy, calculated as the mean deviation from the straight line (the smaller the value, the better the movement control).

This paper presents a single case study in a patient with a C5-C6-C7 BPI who underwent reconstructive surgery before rehabilitation. The rehabilitation was novel in that upper limb robotic

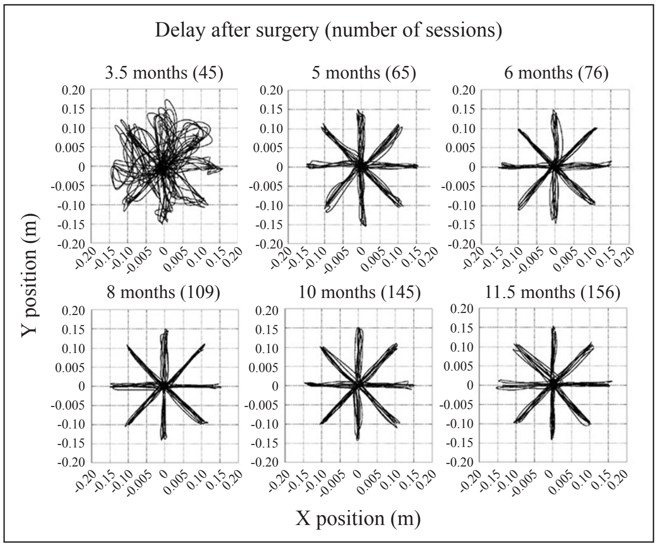

Figure 4.—Hand trajectories during unassisted reaching tasks between 3.5 months after surgery and 11.5 months after surgery; the Y direction represents a forward motion of the patient's arm while the X direction laterally moves the patient's arm in front of him.

therapy was added to usual rehabilitation with good tolerance. This study reports the results of an objective kinematics-based motor assessment that complemented the clinical evaluation and characterized motor recovery. The results demonstrated that while changes in MRC scores were very small during the first 6 months after surgery, motion kinematics improved markedly. This tool is sensitive and can detect small changes in several motor recovery metrics, in contrast with the MRC scale. Although few studies have evaluated rehabilitation after BPI, our results appear consistent with some indications drawn from reviews[5] in which comprehensive rehabilitation programs were compared with usual care are promising. The impact of such an intensive training on motor outcomes is uncertain however comparison with results in the literature suggests that time for re-innervation of the biceps muscle sounds shorter (3 months *vs.* 5/6 months[6]).

The results of this study must be interpreted with caution due to the case study methodology. However, carrying out rigorous clinical studies in patients with BPI is complex because of the small number of adults, of the variability of injury pattern as well as of the current low evidence of the effectiveness of rehabilitation.

This report demonstrates that robotic upper limb rehabilitation used as an adjunct to usual care can be applied safely after surgery for BPI. The robot can be used to objectively assess motor recovery. Whether the training impacted the motor outcomes cannot be determined from that study.

Christophe DURET [1, 2] *, Jean-Noël GOUBIER [3],
Anne RENAUDIN [1], Cyril LEGRAND [1],
Philippe DROUARD [1], Anne-Gaëlle GROSMAIRE [1],
Typhaine KOEPPEL [1]

[1]Unit of Neurological Rehabilitation, Physical Medicine and Readaptation, CRF Les Trois Soleils, Boissise-Le-Roi, France; [2]Service of Neurology, Centre Hospitalier Sud Francilien, Corbeil-Essonnes, France; [3]Institut de Chirurgie Nerveuse et du Plexus Brachial, Paris, France

*Corresponding author: Christophe Duret, CRF Les Trois Soleils, 19 rue du Château 77310 Boissise-Le-Roi, France. E-mail: Ch.duret@les-trois-soleils.fr

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Cancer rehabilitation: closing the gap in low- and middle-income countries

Cancer has emerged as global health problem including in low- and medium-income countries (LMICs). Of the 13 million new cancer cases diagnosis each year, 56% were found in LMICs.[1] The cancer incidence in LMICs is estimated to increase 75% in the next decade. In LMICs, cancers are often diagnosed in late stages with