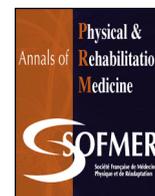




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Letter to the editor

Reorganization of muscle synergies in 2 individuals with C5 and C6 tetraplegia after biceps-triceps and posterior deltoid-triceps tendon



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Dear Editor

Individuals with spinal cord injury (SCI) at the C5 or C6 level will have paralysis of the triceps brachii muscle. Elbow extension can be surgically restored by transferring the tendon of a functioning muscle onto the tendon of the paralyzed triceps brachii. The most frequently transferred tendon [1] is the posterior deltoid tendon [2]. However, if the clavicular head of the pectoralis major muscle is weak, this can create a muscle imbalance around the shoulder girdle [3]. In that case, transferring the biceps brachii tendon is recommended [4]. The success of this intervention relies on the ability of the patient to dissociate the drive between the transferred biceps brachii and the other elbow flexor muscles [1].

Even though tendon transfers are widely used to improve upper-limb function in individuals with tetraplegia, the subsequent reorganization of muscle patterns has been little studied. The identification of muscle synergies, defined as groups of muscles activated in synchrony [5], from electromyographic (EMG) signals may help to provide a deeper understanding of changes in muscle patterns. The aim of this study was to investigate the reorganization of muscle patterns after surgical restoration of elbow extension by the identification of muscle synergies, for the first time.

Three participants voluntarily took part in this study and provided informed consent after the local human research ethics committee approved the study: a healthy 21-year-old man (healthy control); a 20-year-old man with C5 tetraplegia (patient-biceps), ASIA Impairment Scale (AIS) A; and a 24-year-old man with C6 tetraplegia (patient-deltoid), AIS B. The demographic and clinical characteristics of the 2 patients are summarized in Table 1. Patient-biceps underwent a biceps brachii tendon transfer [4] and patient-deltoid underwent a posterior deltoid tendon transfer [2].

Muscle patterns were evaluated once for the healthy control and twice for the patients: before the surgery and after 5 months of rehabilitation. The procedure consisted of consecutive elbow extension-flexion cycles with the shoulder externally rotated and held in 60° and 120° of abduction by the experimenter. For the patients, elbow extension was only possible at 60° of abduction preoperatively; however, 5 months after tendon transfer, elbow extension was also possible at 120° of shoulder abduction. Surface EMG measurements were collected for the biceps brachii, brachialis, brachioradialis, and anterior, middle and posterior deltoid muscles for all participants. EMG activation of the triceps brachii muscle was also recorded in the healthy control.

EMG data were recorded by using a 16-channel system (WaveWireless EMG, Cometa, Milan, Italy) at 1000 Hz. EMG signals were band-pass-filtered (4th order Butterworth, 10–450 Hz), full-wave-rectified, and smoothed with a low-pass filter (10 Hz). EMG amplitude was normalized to its peak value across all trials for each session and each muscle. Each elbow extension-flexion cycle was interpolated to 100 time points such that extension corresponded to 0 to 50% of the cycle and flexion to 50% to 100%.

For each participant and each movement, all combinations from 1 to 7 muscle synergies (because the activity of 7 muscles was recorded) were identified by using non-negative matrix factorization (NMF) from the EMG data and data were then averaged across the cycles (mean [SD]: 6.3 [2.6] cycles). Only 2 cycles were available for the patient-biceps preoperatively owing to a technical difficulty. Information about NMF can be found in [8,9]. The algorithm decomposes EMG data into sets of two components: muscle synergy weights $w_{Muscle M}^{Synergy S}$, that represent the relative weighting of each muscle within each synergy, and a synergy activation coefficient, $C^{Synergy S}$, that represents the recruitment of the muscle groups throughout the cycle, so that the activation of each muscle $M =$

$$\sum \text{number of synergies } C \frac{Synergy S}{Muscle M} * W Synergy S + error.$$

The error is the difference between the recorded EMG data and the EMG data reconstructed from the synergies. The NMF algorithm first tests random initial estimates of W and C and via an iterative optimization, selects the matrices of W and C that minimize the sum of the squared error. The extraction of fewer muscle synergies increases the amount of error. We extracted the number of synergies that explained at least 90% of the total variance in the EMG data [10]. Synergies using NMF were calculated with Matlab (MathWorks, Natick, MA, United States) and an open-source Matlab routine [9].

After 5 months of rehabilitation after the tendon transfers, both patient-biceps and patient-deltoid could actively extend their

Table 1

Demographic and clinical data of the 2 patients with spinal cord injury (SCI). The international standards for neurological classification of SCI of the American Spinal Injury Association (ASIA) and International Spinal Cord Society (ISICOS) were used to characterize the neurological status of patients [6]. The ASIA impairment scale (AIS) was used to describe the completeness of injury. The “Giens” classification for the upper limb of patients with tetraplegia is also presented [7].

	Patient-biceps	Patient-deltoid
Age, years	20	24
Weight, kg	65	54
Height, m	1.72	1.60
Cause of SCI	Diving accident in shallow water	Acute transverse myelitis
Associated injuries	None	None
Side of tendon transfer	Right	Right
Type of surgery	Zancolli	Moberg
	Biceps brachii	Posterior deltoid
Time from SCI to surgery, months	25	150
Transfer previously performed on opposite limb	Yes	Yes
	Zancolli-19 months	Moberg-136 months
AIS	A	B
Motor level (right upper limb)	C5	C6
Motor score (right upper limb)	5/25	10/25
Sensory level (right upper limb)	C4	C6
Grade on the “Giens” classification	1	3

AIS: ASIA Impairment Scale; SCI: spinal cord injury.

elbows, with strength ratings of 4 and 3, respectively, on the modified Medical Research Council Scale [11].

Two muscle synergies explained more than 90% of the variance of the original EMG signals, except for the healthy control during the trial at 60° of shoulder abduction, for patient-biceps preoperatively during the trial at 60°, and for patient-biceps postoperatively during the trial at 120°, for which 2 muscle synergies explained 88.9%, 89.7% and 88.4%,

respectively, of the variance of the original EMG signals. Considering the closeness of the numbers to 90%, 2 muscle synergies were analyzed in all cases. In all cases, the $C^{Synergy1}$ was mainly activated during extension. In the healthy control, this synergy was represented by the triceps and deltoid muscles (extension synergy). $C^{Synergy2}$ was mainly activated during flexion. In the healthy control, this synergy (flexion synergy) was represented by the flexor muscles (biceps,

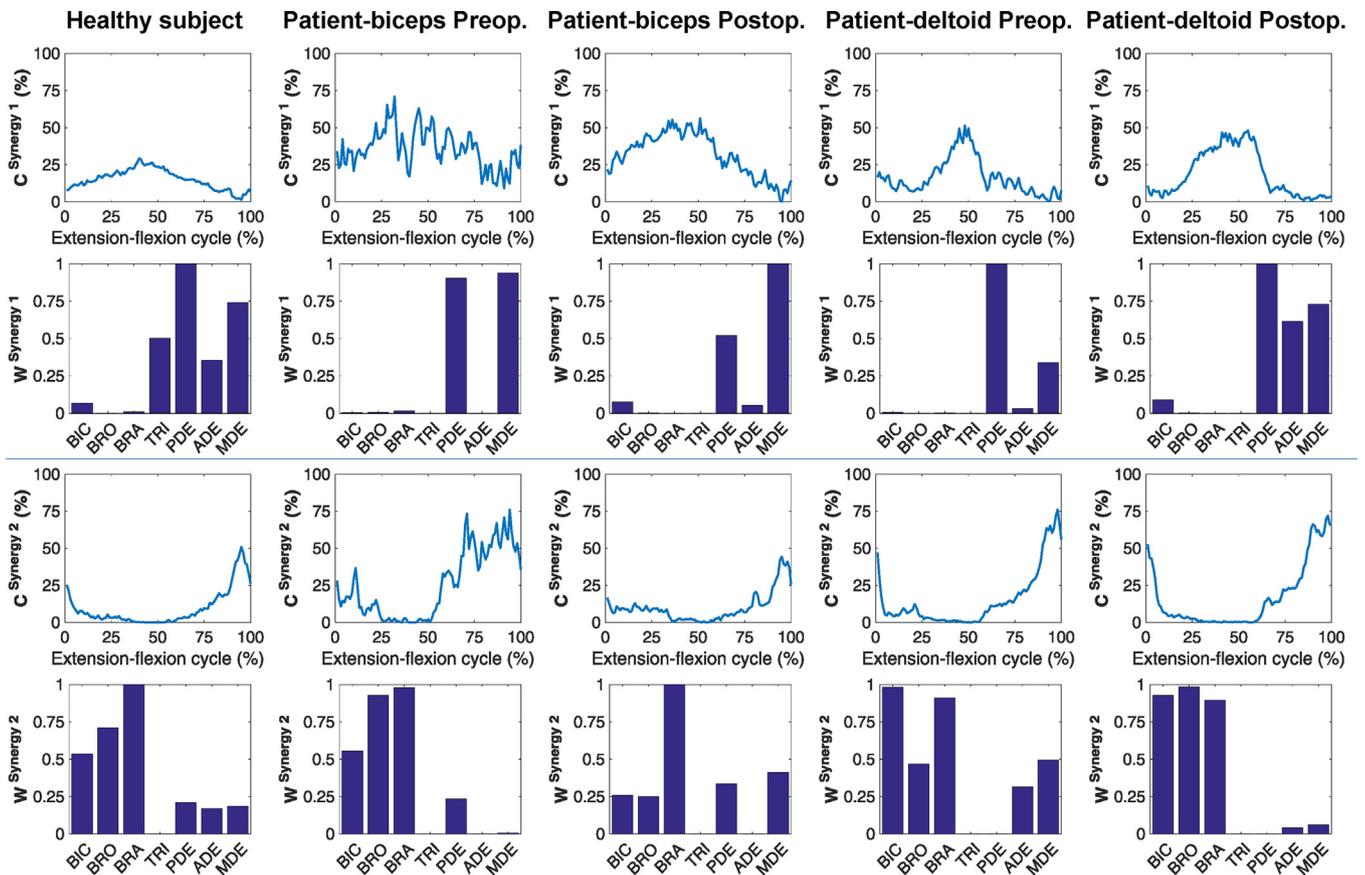


Fig. 1. Muscle synergies for elbow extension-flexion movements with the shoulder abducted at 60° for the healthy control subject, patient-biceps before and after biceps brachii tendon transfer, and patient-deltoid before and after posterior deltoid tendon transfer. The decomposition algorithm has 2 components: muscle synergy weights, $w_{Muscle}^{Synergy}$ (no unit), that represent the relative weighting of each muscle within each synergy and a synergy activation coefficient, $C^{Synergy}$ (%), that represents the activation of muscle groups across the cycle. BIC, biceps; BRO, brachioradialis; BRA, brachialis; TRI, triceps; PDE, posterior deltoid; ADE, anterior deltoid; MDE, middle deltoid; Preop., preoperative data; Postop., postoperative data.

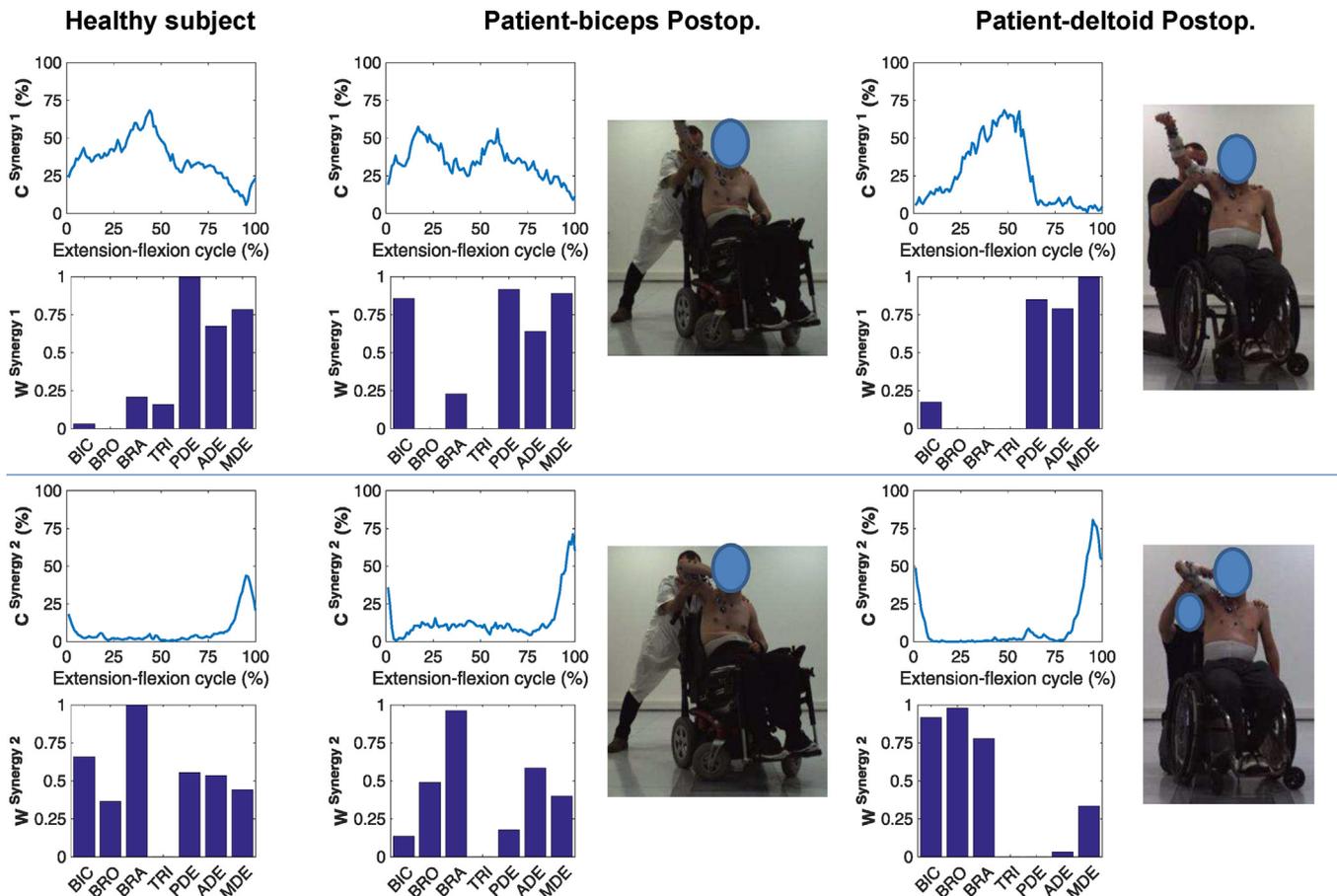


Fig. 2. Muscle synergies for elbow extension-flexion movements with the shoulder abducted at 120° for the healthy control subject, patient-biceps after biceps brachii tendon transfer, and patient-deltoid after posterior deltoid tendon transfer, supplemented with the frontal views of patient-biceps (left) and patient-deltoid (right) performing active extension (top) and flexion (bottom) with the shoulder abducted at 120°. BIC: biceps; BRO: brachioradialis; BRA: brachialis; TRI: triceps; PDE: posterior deltoid; ADE: anterior deltoid; MDE: middle deltoid; Preop.: preoperative data; Postop.: postoperative data.

Table 2
Muscles involved each synergy for the 3 participants.

	Synergy 1 (elbow extension)	Synergy 2 (elbow flexion)	Both synergies (hypothesized as shoulder stabilization)
Healthy control	Triceps	Biceps; brachialis; brachioradialis	ADE; MDE; PDE
Patient-biceps			
Preop.	MDE; PDE	Biceps; brachialis; brachioradialis	///
Postop.	Biceps (neo-triceps)	Brachioradialis; brachialis	ADE; MDE; PDE
Patient-deltoid			
Preop.	PDE	ADE; biceps; brachialis; brachioradialis	MDE
Postop.	ADE; MDE; PDE (neo-triceps)	Biceps; brachialis; brachioradialis	///

ADE: anterior deltoid; MDE: middle deltoid; PDE: posterior deltoid.

brachioradialis and brachialis) and, with a lower weight, the deltoid muscles (Figs. 1 and 2).

Patient-biceps: preoperatively, the posterior and middle deltoids were the only 2 muscles in the extension synergy, and the 3 elbow flexors weighted in the flexion synergy (Fig. 1). Postoperatively, at 60°, the extension synergy was unchanged, and the flexion synergy showed the emergence of the posterior and middle deltoids and the decrease in weights of the biceps and brachioradialis (Fig. 1). Post-operatively, at 120°, the 3 heads of the deltoid were involved in both synergies, together with the transferred biceps in the extension synergy and the 2 other elbow flexors in the flexion synergy (Fig. 2).

Patient-deltoid: preoperatively, the posterior deltoid was present in the extension synergy, the anterior deltoid in the flexion

synergy, and the middle deltoid in both synergies. Postoperatively, all 3 heads of the deltoid were exclusively active during the extension synergy. The elbow flexors were included only in the flexion synergy both pre- and postoperatively (Figs. 1 and 2).

The muscles involved in each synergy are summarized in Table 2 for the 3 participants.

In this study, we used a factorization technique to identify changes in muscle synergies after surgical restoration of elbow extension in 2 patients with tetraplegia. As expected, during the elbow extension-flexion task, 2 synergies were identified in the healthy control: an extension synergy, composed of the elbow extensor muscles, and a flexion synergy, composed of the elbow flexor muscles. The 3 heads of the deltoid were involved in both synergies, likely to stabilize the shoulder at the instructed abduction

angle. Before the tendon transfer and despite paralysis of the elbow extensor muscles, both patients were able to perform the cyclical elbow extension–flexion task with the shoulder abducted at 60°, probably with the help of gravity. The posterior and middle deltoids may also have helped in the extension movement, because they were more involved in the extension than for the healthy control.

After tendon transfer and 5 months of rehabilitation, both patients were able to perform active elbow extension against gravity. Analysis of the muscle synergies showed that the transferred muscles of both patients became largely predominant in the extension synergy, thus demonstrating the effectiveness of the tendon transfers.

Patient-biceps clearly succeeded in dissociating the drive between the transferred biceps brachii and the other elbow flexor muscles during elbow extension–flexion against gravity. During the trial at 60° of shoulder abduction, the weighting of the biceps during extension was low: this finding confirmed no need for the presence of an extensor to perform the extension–flexion task at 60° of shoulder abduction. In both trials, there was a low weighting of the biceps in the flexion synergy: this finding could reveal a small co-contraction of the biceps with the elbow flexors during elbow flexion, which was not detrimental to function because elbow flexion and extension were efficient in patient-biceps postoperatively. Of note, the weightings of posterior and middle deltoids increased in the flexion synergy postoperatively to a level similar to the healthy control. We assume that the prevalence of the middle and posterior deltoids during extension preoperatively was part of a compensation strategy to perform extension without an extensor. After the transfer of the biceps brachii, this strategy was no longer necessary and thus the weightings of posterior and middle deltoids were balanced between extension and flexion as for the healthy control.

However, patient-deltoid exhibited a simplified motor control strategy after the tendon transfer as the 3 heads of the deltoid became synergistic and exclusively involved in the extension synergy. Strong co-activation of the 3 heads of the deltoid during extension indicates unbalanced activity around the shoulder joint. However, we do not know whether this co-activation results from an inability to dissociate the drive to the different heads of the deltoid, leading to imbalance, or is a co-contraction strategy to stabilize the shoulder joint. This question needs to be explored in further research involving additional EMG measurements of main shoulder stabilization muscles, such as infraspinatus, supraspinatus and subscapularis muscles.

This study is a case report of 2 patients with SCI who underwent tendon transfer. The aim was to highlight the utility of identifying muscle synergies to investigate the reorganization of muscle patterns and not to compare the effectiveness of tendon transfer techniques. Indeed, the differences in reorganization of muscle patterns found in the 2 patients may also be due to their differences in motor level, because they did not have the same preserved muscles, and their differences in sensory level, even if we expect that the lack of sensory input had a relatively small effect on the results because the studied movements were not fine motor activities [12]. Therefore, our findings from this case report cannot be generalized to patients with SCI undergoing tendon transfer surgery.

Muscle synergy analysis must not be used as a single measure of surgical outcome. This method provides additional quantitative information relating to muscle patterns, which is complementary to existing clinical measures [13].

Finally, the methods used to calculate muscle synergies likely affected the results [10]: EMG filtering, EMG temporal normalization, EMG amplitude normalization, number of muscles recorded, number of movement cycles and the consideration of synergies that explained at least 90% of the total variance in muscle activation, as is commonly found in the literature [10]. Until now, no study has justified this choice [10], which may therefore be

open to question. However, the same methodological conditions were used for all 3 participants.

This study demonstrated that muscle patterns are reorganized after surgical restoration of elbow extension. Muscle synergy analysis is a powerful tool:

- it is non-invasive;
- EMG activity is recorded from numerous muscles and described in an integrative fashion;
- differences can be detected between patients as well as after surgery to restore movement. Future studies should evaluate the time-course of changes during postoperative rehabilitation.

Disclosure of interest

The authors declare that they have no competing interest.

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Aurélie Sarcher^{a,*}, Brigitte Perrouin-Verbe^a, Sophie Touchais^b,
Guillaume Gadbled^b, Matthieu Gahier^a, Sylvain Brochard^c,
François Hug^d, Raphaël Gross^a

^aMotion analysis laboratory, Physical Medicine and Rehabilitation,
University Hospital of Nantes, 44093 Nantes, France

^bOrthopaedic Surgery and Traumatology, University Hospital of Nantes,
44000 Nantes, France

^cLaboratory of Medical Information Processing (LaTIM), INSERM UMR
1101, 29609 Brest, France

^dLaboratory of Movement–Interactions–Performance (MIP), EA 4334,
University of Nantes, 44322 Nantes, France

*Corresponding author. Laboratoire d'Analyse du Mouvement,
Hôpital Saint-Jacques, 85, rue Saint-Jacques, 44093 Nantes cedex,
France

E-mail address: aurelie.sarcher@gmail.com (A. Sarcher).