Chapter

A Funhouse Mirror: Muscular Co-Contractions as a Reflection of a Spontaneous Aberrant Regeneration of the Brachial Plexus Injury in the Adults - Anatomical Background, an Attempt to Classify and Their Clinical Relevance within the Reconstruction Strategies

Alexander A. Gatskiy and Ihor B. Tretyak

Abstract

A certain number of spontaneously recovering birth injuries to the brachial (BPI) plexus are known to be accompanied by muscle co-contractions (Co-Cs). The process of aberrant spontaneous regeneration contributes to the appearance of this phenomenon. Treatment strategies are mostly narrowed down to temporarily "switching off" the antagonist, allowing the agonist to perform. Less is known about the incidence of BPI-associated Co-Cs in adults (a-BPI), the control of which mainly presumes the extrapolation of a treatment strategy that has been shown to be effective in infants. Nowadays, surgical reconstruction of independent elbow flexion at BPIs relies heavily on redirection (transfer) of nerves that produce their own Co-Cs. These induced Co-Cs could potentially be reduced. Selecting the appropriate nerve transfer strategy (when the donor pool is narrowing), with its potential impact on the already complex and intricate global and segmental biomechanics of the upper extremity, becomes challenging. The chapter presents the anatomical background for the occurrence of muscular Co-Cs, a work on clinical classification of both regeneration associated and induced Co-Cs, possible surgical strategies, their benefits and limitations, in the presence of regeneration-associated muscle Co-Cs at a-BPI and clinical examples.

Keywords: adult brachial plexus injury, nerve transfer, medial pectoral nerve, oberlin transfer, musculocutaneous nerve, co-contraction

1. Introduction

Brachial plexus injury (BPI) in adults (a-BPI) remains one of the leading causes of permanent and severe disability among all injuries in the peripheral nervous system [1]. The evolution of treatment options from neurolysis through nerve grafting to nerve transfers has led to dramatic improvements in functional outcomes [2]. The timing of the surgical reconstruction has always been strongly dependent on the process of spontaneous regeneration [3]. As the time allotted for spontaneous regeneration passes and no clear clinical and electrophysiological signs of regeneration are seen, the majority of surgeons advocate for active surgical reconstruction [4].

The dynamics of spontaneous regeneration are well described in newborns with obstetric BPI [4, 5]. It is often accompanied by co-contractions (Co-C) of *de novo* reinnervated muscles [6], which respond well to injections of botulinum toxin A [7]. Less information can be found concerning the management of the Co-C in cases of a-BPI [8].

A rational explanation of the origin of the Co-Cs could be a change in the predominance of root representation within the muscles of the upper extremity in the case of BPI (**Figure 1**). This predominance is present both under normal conditions (known as "luxury innervation" [9]) and becomes more evident under the described [10, 11] pathological conditions (known as injury/regeneration associated "simple and complex misdirection"). For instance, at nonfunctioning C5-C6 rootlets greater pectoral, triceps brachii, latissimus dorsi muscles, etc. receive motor fascicles from C7-8-Th1, thus, have or receive closely adjoined motor cortex representation. The activation of the closely adjoined motor cortex during voluntary contraction could possibly lead to their co-activation Co-C. The clinically apparent expression of Co-C most probably depends on how close the cortical centers are situated. Functional MRI (cortical mapping) findings partially explain this process [12].

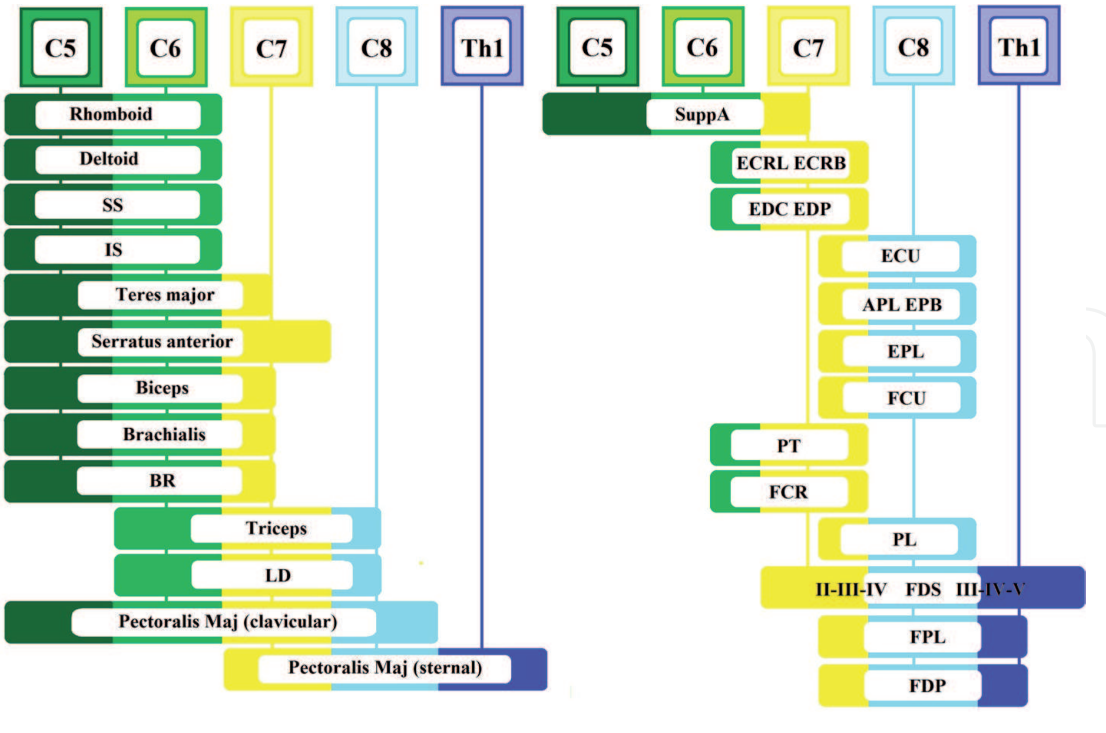

Figure 1.
Normal representation of the roots' of the brachial plexus within the muscles of the upper extremity (a similar color represents the same innervation pattern or representation of roots in the muscles and is most likely responsible for the occurrence of co-contraction(s)). SS—suprascapular muscle; IS—infrascapular muscle; BR—brachioradialis; LD—latissimus dorsi muscle; SuppA—supinator antebrachii muscle; ECRL—extensor carpi radialis longus; ECRB—extensor carpi radialis brevis; EDC—extensor digitorum communis; EDP—extensor indicis and digiti minimi; ECU—extensor carpi ulnaris; APL—abductor pollicis brevis; EPB—extensor pollicis brevis; EPL—extensor pollicis longus; FCU—flexor carpi ulnaris; PT—pronator teres muscle; FDS—flexor digitorum superficilalis; FPL—flexor pollicis longus; FDP—flexor digitorum profundus.

2. From clinical observations to systematic approach to classification: what we know exactly

To date, there is no classification of muscular Co-Cs of the upper extremity associated with *"aberrant spontaneous"* BPI recovery. Later descriptions of this pathologic motor phenomenon are narrowed to so-called "triceps syndrome" [13], which includes co-activation of both biceps and triceps brachii muscles *"antagonistic"* Co-C (**Table 1**). However, other types of co-activation have not received much attention, regardless of the fact that they potentially could severely entangle the biomechanics of the proximal and distal segments of the upper extremity. The clinically observed *"proximal-proximal"* Co-C (**Table 1**) related to "triceps syndrome" includes also simultaneous activation of the triceps brachii and greater pectoral muscle *"non-antagonistic"* (**Table 1**). Even less is known about the distal projection of "triceps syndrome" on the functions of the wrist and fingers. The clinical observations that have already been made have not yet been reflected in any type of scientific literature. Still, elbow, wrist, and finger extension, or *"proximal-distal"* Co-C (**Table 1**) is not uncommon. Technically, this type of co-activation is not a pure Co-C, hence the wrist and finger extension does not occur simultaneously, but rather sequentially in relation to the contraction of the triceps brachii muscle. Yet it is still present within the clinical picture of "triceps syndrome" and dramatically entangles wrist/hand function and stability.

Currently, injuries to BPI are mainly treated with nerve transfers (NT) [14]. The pool of traditional extra- and intraplexal donor nerves could be narrowed due to cranially (involvement of C4) and/or caudally expanded (involvement of C7-8) BPI, respectively. In most cases, it consists of Oberlin [15], double-fascicular [16], and medial pectoral [12] NTs.

It is well known that any type of NT, especially when a donor-nerve provides motor fascicles to more than a single muscle, could potentially produce co-activation (*"induced"* Co-C **Table 1**) of other muscles related to the donor's nerve during the early stages of clinically visible regeneration [17]. Reduction of this type of co-activation is achieved through active rehabilitation programs [17]. Most of the programs are aimed at dissociating the voluntary activation of the newly obtained function from the entire area of the cortical representation of the donor nerve [17]. The widespread adoption of NTs among the surgical society quickly isolated a pool of unwanted NTs. These NTs were able to produce induced Co-C [18] and were mostly related to the

Aberrant spontaneous		**Induced**	
Proximal-Proximal	*Example: BB-TB-Pct*	**Proximal-Proximal**	*Example (nerves): Pct-BB (PM-MCN)*
Proximal-Distal*	*Example: TB-ECRB/L*	Proximal-Distal	*Example (nerves): FCU/FDP4–5-BB (UN-MCN)*
Distal-Distal*	*Example: WE-FE*	Distal-Distal	*Example (Nerves): FCR-EDC (MN-PIN)*
Antagonistic	*Example: BB-TB*	Extraplexal	*Example (nerves): Diaphr.-BB (PhN-MCN)*
Non-antagonistic	*Example: TB-Pct*	Intraplexal	*Example (nerves): any known*
Only intraplexal	*Example: any known*	Antagonism**	*Example**:?*

BB—biceps brachii muscle; Pct—greater pectoral muscle; TB—triceps brachii muscle; ECRB/L—extensor carpi radialis brevis et longus; WE—wrist extensors; FE—finger extensors; FCU—flexor carpi ulnaris; FPD4–5—deep flexors of 4–5 fingers; EDC—extensor digitorum communis; Diaphr.—diaphragm; PM—pectoral nerves; MCN—musculocutaneous nerve; UN—ulnar nerve; MN—median nerve; PIN—posterior interosseous nerve.
**Sequential Co-C (see description in the text)*
***Unknown.*

Table 1.
Work classification of known Co-Cs.

forearm (*"distal-distal"* Co-C **Table 1**). In most cases, attempts to dissociate them were unsuccessful and severely confounded the hand-wrist biomechanics [18].

Reconstructions strategies in BPI are prioritizing the reanimation of the elbow flexion [3, 19]. Active surgical reconstruction, with both tendon and NTs, provides active elbow flexion in either earlier or later terms [8]. The general principles of NTs are well known [20]. Reconstruction strategies of BPI are strongly dependent on the selection of an appropriate donor nerve, considering the possible functional advantages and disadvantages of each.

Hence, the evaluation of the efficacy of any type of NT is generally narrowed to the identification of either a muscular power (MRC) or a change in a joint angle produced by the recovered muscle, Oberlin or double-fascicular NT have become most popular and have established themselves as a "golden standard" [2]. The induced *"proximal-distal"* (**Table 1**) Co-C, which follows the abovementioned procedures, is one of those that are easily nullified even without any extensive reeducation [17].

On the other hand, the influence of a nerve transfer on the intimate biomechanical correlation between the upper arm and hand movements is underestimated in most cases. Only a few publications have attempted to characterize and define the real meaning of this coordination and the influence of induced proximal-distal co-activation on the affected limb on a global scale [17]. Escudero et al. [17] discovered that at least 39% of patients who received Oberlin transfer were unable to dissociate elbow flexion from wrist/finger flexion. From a biomechanical point of view, this meant that it deeply "confounded" the function of the hand during daily activities [17].

The interaction between aberrant and induced Co-C in the case of BPI, its influence on the global biomechanics of the upper extremity has not received any reflection in the scientific literature at all. This is most likely due to its extremely rare occurrence among all cases of a BPI. Moreover, since the use of reconstructive strategies presumes the return of lost functions and the preservation (or at least not the loss of the majority) of the preserved ones, the following clinical examples could potentially be of great interest.

3. Clinical examples

3.1 Clinical example 1

A 26-year-old man was admitted to our department 2 mos. after a traction-type injury to his right brachial plexus in a motorcycle accident; neurological examination revealed complete injury to the right brachial plexus. A C5-6-7-8 avulsion with no cranial expansion and preserved function to n.phrenicus (C4) was confirmed during the explorative surgery. None of the intra-plexal motor donor nerves were available for transfer at the time of surgery. In order to reanimate active elbow flexion, NT of n.phrenicus to the musculocutaneous nerve (distally to the branches of the coracobrachialis muscle) through approx. 12 cm sural nerve graft was performed. Another NT of the accessory to the suprascapular nerve [21] was performed to reanimate abduction and external rotation of the shoulder.

Physiotherapy was resumed 6 weeks later. 13 mos. after surgery, shoulder abduction (frontal plane) and external rotation were 80° and 40°, respectively. BB recovered to M4 and elbow flexion was near 90°, was associated with breathing "breathing hand" *induced Co-C*. Voluntary elbow flexion appeared on the 16th mo. and could be controlled consciously. 19 mos. after the surgery, we observed the recovery to the function of the greater pectoral muscle (M4), which was associated with ineffective (less than M2) function to FDPs - *aberrant spontaneous proximal-distal Co-C (Pct-FF)* (**Figure 2**). A T-shaped wrist plate and trapeziometacarpal

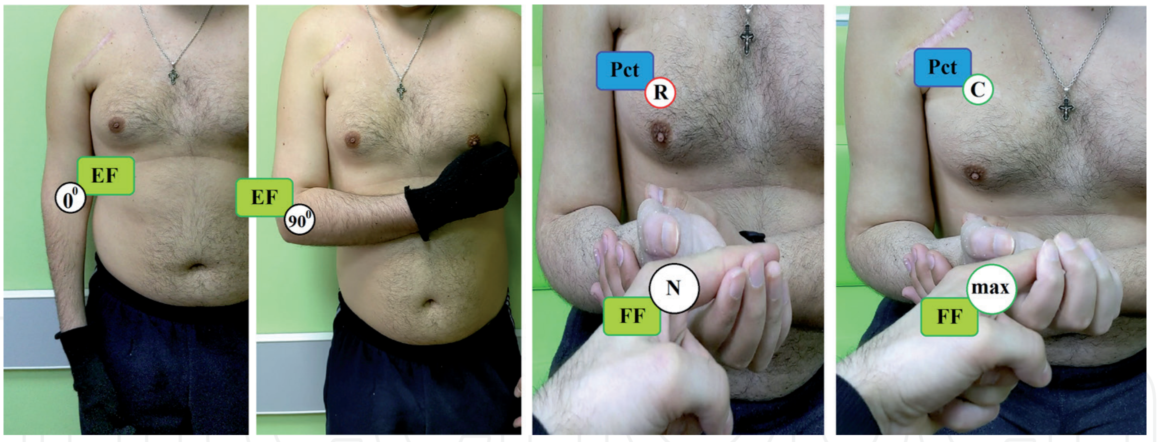

Figure 2.
"Breathing hand" andcorrelation between greater pectoral muscle function and finger flexion (late proximal-distal Co-C). EF—elbow flexion; Pct—greater pectoral muscle, FF—finger flexion; N—neutral position; R—rest; C—maximal contraction; max—maximal finger flexion/transverse volar grip.

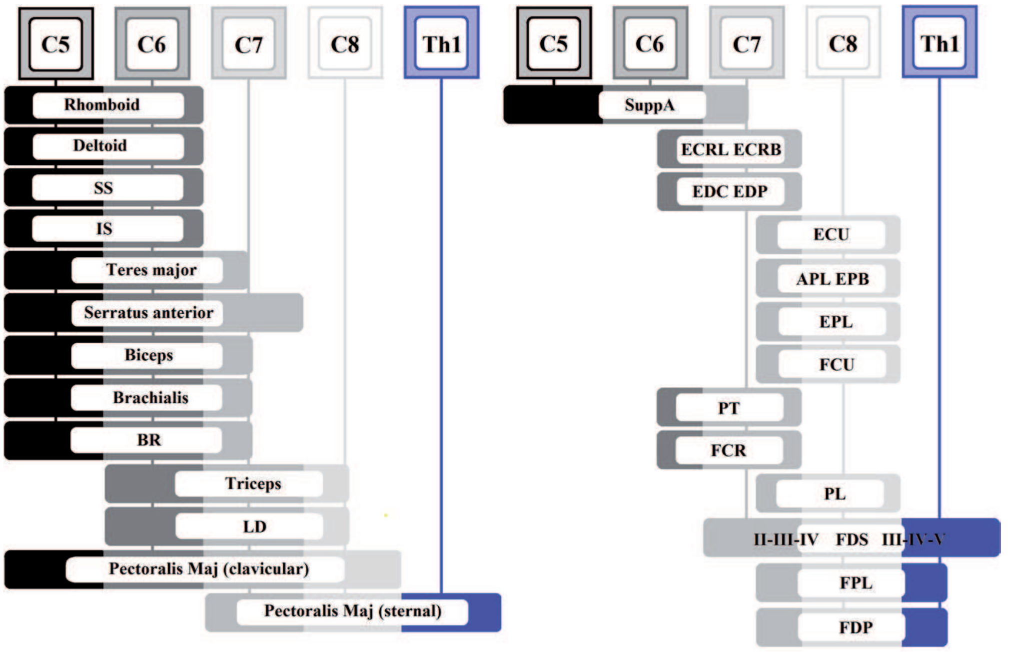

Figure 3.
Schematic explanation of the occurrence of late proximal-distal Co-C (Pct-FF) associated with aberrant spontaneous regeneration of initially complete a-BPI (a similar color represents the same innervation pattern or representation of roots within muscles and is most likely responsible for the emergence of co-contraction). SS—suprascapular muscle; IS—infrascapular muscle; BR—brachioradialis; LD—latissimus dorsi muscle; SuppA—supinator antebrachii muscle; ECRL—extensor carpi radialis longus; ECRB—extensor carpi radialis brevis; EDC—extensor digitorum communis; EDP—extensor indicis and digiti minimi; ECU—extensor carpi ulnaris; APL—abductor pollicis brevis; EPB—extensor pollicis brevis; EPL—extensor pollicis longus; FCU—flexor carpi ulnaris; PT—pronator teres muscle; FDS—flexor digitorum superficilalis; FPL—flexor pollicis longus; FDP—flexor digitorum profundus.

arthrodesis were performed to ensure the stability of the hand, and active rehabilitation started 4 weeks after the surgery. The patient was instructed to navigate the finger flexion by actively contracting the greater pectoral muscle with maximum effort. 24 mos. after the initial surgery, the FDP power increased to M3–4, allowing the patient to perform an effective transverse volar grip.

Rational explanation: It is not uncommon for some muscle groups to regenerate to a certain degree in many later terms after complete injury to the brachial plexus. Most often, regeneration in the case of complete a-BPI occurs in a greater pectoral muscle. Acting as an internal rotator of the shoulder, its function disables "sagittalization" of the upper arm and forearm during the basic activities of daily living

(ADLs), especially when external rotators are non-functional or regenerated to a much lesser extent in terms of power. The shortening of the muscle and tendon structures surrounding the glenohumeral joint confirms this functional misposition. Only a small number of complete a-BPIs show muscle regeneration on any surface of the forearm, even rarely to hand intrinsics. It is a common occurrence, and this clinical example confirms that late spontaneous regeneration of both the greater pectoral and forearm muscles is accompanied by their co-activation. Technically, this type of co-activation does comply with the previously classified subtypes (**Table 1**) and comprises the characteristics of "*proximal-distal non-antagonistic Co-C*". The explanation for the occurrence of this late Co-C lies most probably within the innervation pattern of the aforementioned muscles (**Figure 3**).

Conclusion: The recovered function of the greater pectoral muscle serves as an indicator of a likelihood of recovery of other distal muscles (forearm) of the upper extremity, playing a leading role in a co-activation pair in this particular case the greater pectoral muscle helped to navigate the contraction of the FDPs, providing not only clinically visible feedback but also an EMG-assisted video-feedback during active rehabilitation.

3.2 Clinical example 2

A 28-year-old man was admitted to our department 3 mos. after a traction-type injury to the left brachial plexus in a motorcycle accident; neurological examination revealed the complete injury to the left brachial plexus. A C5-6 avulsion with no cranial expansion and preserved function to n.phrenicus (C4) was confirmed during the explorative surgery. None of the intraplexal motor donor nerves were available for transfer at the time of surgery. In order to reanimate active elbow flexion, NT of n.phrenicus was transferred to the musculocutaneous nerve (distally to the branches of the coracobrachialis muscle) through a sural nerve graft approximately 12 cm long. Two other NTs were performed to reanimate flexion, abduction, and external rotation of the shoulder: pars sternocleidomastoideus of the accessory nerve to the axillary nerve through approx. 14 cm sural nerve graft and suprascapular nerve [21] NT, respectively.

Physiotherapy was resumed 6 weeks later. 17 mos. after surgery, shoulder abduction (frontal plane) was 90°. BB recovered to M4, and elbow flexion was near 110°, was associated with breathing—the "breathing hand" *induced Co-C.* Voluntary elbow flexion could be controlled consciously 24 mos. after surgery, we observed the recovery of function of the greater pectoral muscle (M4), which was associated with the effective (M4) function of ECRB—*aberrant spontaneous proximal-distal Co-C (Pct-WE)* (**Figure 4**). A T-shaped wrist plate and a trapeziometacarpal arthrodesis were performed to ensure wrist stability, followed by a rigid cast

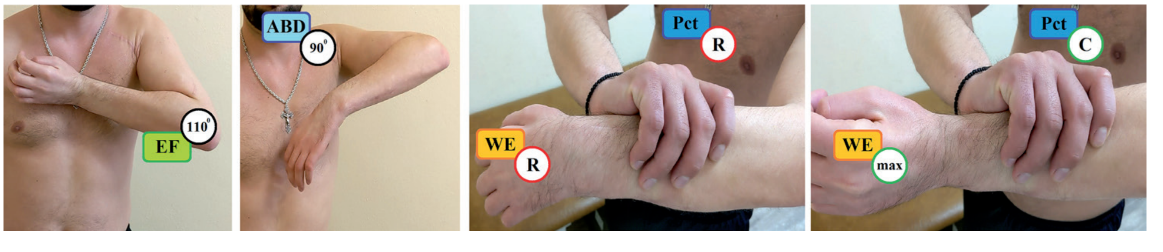

Figure 4.
"Breathing hand", shoulder abduction and correlation between greater pectoral muscle function and wrist extension (late proximal-distal Co-C before wrist arthrodesis). EF—elbow flexion; ABD—shoulder abduction; Pct—greater pectoral muscle, WE—wrist extension; R—rest; C—maximal contraction; max—maximal wrist extension mediated by ECRB.*

immobilization for the next 2 mos. Recovered function to ECRB associated with late *aberrant spontaneous proximal-distal Co-C (Pct-WE)* will be used for a tendon transfer to restore FDP/FPL function at a later date.

Rational explanation: It is not uncommon for some muscle groups to regenerate to a certain degree at a later date after complete injury to the brachial plexus. Most often, regeneration at complete a-BPI occurs in the greater pectoral muscle. Acting as an internal rotator of the shoulder, its function disables "sagittalization" of the upper arm and forearm during basic activities of daily living (ADLs), especially when external rotators are non-functional or are regenerated to a much lesser extent in terms of power. The shortening of the muscle and tendon structures surrounding the glenohumeral joint confirms this functional misposition. Only a small number of complete a-BPIs show muscle regeneration of either surface of the forearm, even rarely to hand intrinsics. This is a common occurrence, and this clinical example confirms that late spontaneous regeneration of both the greater pectoral and forearm muscles is accompanied by their co-activation. Technically, this type of co-activation does comply with previously classified subtypes (**Table 1**) and comprises the characteristics of "*proximal-distal non-antagonistic Co-C*". The explanation for the occurrence of this late Co-C lies most probably within the innervation pattern of the aforementioned muscles (**Figure 5**).

Conclusion: The recovered function of the greater pectoral muscle serves as an indicator of the likelihood of recovery of other distal muscles (forearm) of the upper extremity, which plays a leading role in co-activation pair; in this particular case, the greater pectoral muscle helped to navigate the contraction of ECRB and ECRL, providing not only clinically visible feedback, but also an EMG-assisted video-feedback during active rehabilitation. The increased power to ECRL/ECRB was only possible due to the helping assistance of the much earlier regenerated greater pectoral muscle.

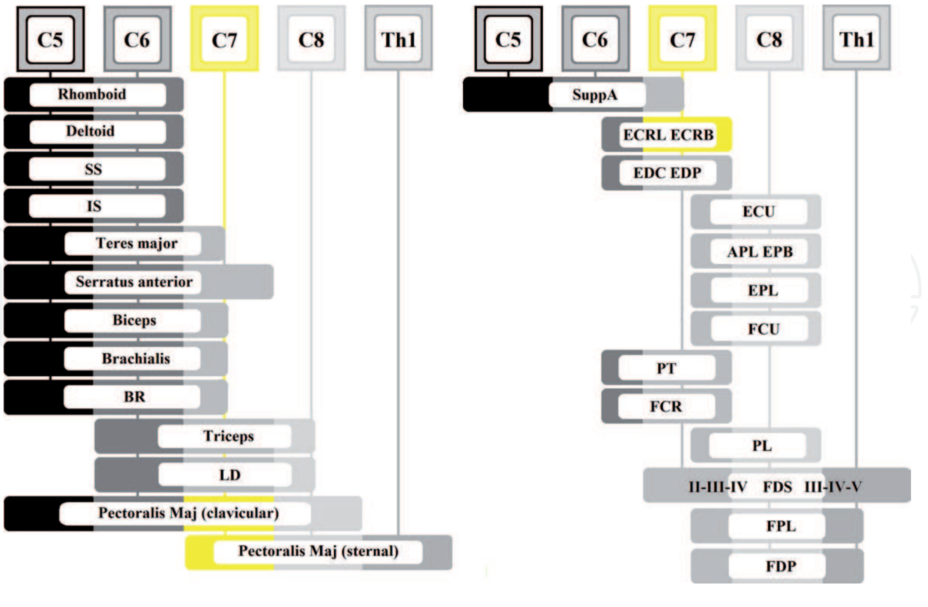

Figure 5.
Schematic explanation of the occurrence of late proximal-distal Co-C (Pct-WE) associated with aberrant spontaneous regeneration of initially complete a-BPI (a similar color represents the same innervation pattern or root representation within the muscles and is most likely responsible for the emergence of co-contraction). SS—suprascapular muscle; IS—infrascapular muscle; BR—brachioradialis; LD—latissimus dorsi muscle; SuppA—supinator antebrachii muscle; ECRL—extensor carpi radialis longus; ECRB—Extensor carpi radialis brevis; EDC—Extensor digitorum communis; EDP—Extensor indicis and digiti minimi; ECU—Extensor carpi ulnaris; APL—Abductor pollicis brevis; EPB—Extensor pollicis brevis; EPL—extensor pollicis longus; FCU—flexor carpi ulnaris; PT—pronator teres muscle; FDS—flexor digitorum superficilalis; FPL—flexor pollicis longus; FDP—flexor digitorum profundus.

3.3 Clinical example 3

A 33-year-old man was admitted to our department 5 mos. after a traction-type injury to the left brachial plexus in a motorcycle accident; neurological examination revealed non-functioning supraspinatus and infraspinatus, teres major and minor, deltoid and serratus anterior, biceps brachii (BB), coracobrachialis and brachialis muscles (0 points on the MRC scale—M0); latissimus dorsi muscle—M3; greater pectoral (Pct), all heads of triceps brachii (TB) muscles—M4; wrist (WE) and finger (FE) extensors—M4; wrist and finger flexors, intrinsics of the hand—M5. Clinically visible *aberrant spontaneous proximal-proximal non-antagonistic Co-C (Pct-TB)* and *aberrant spontaneous proximal-distal Co-C (TB-WE + FE)* were present. The projection of the innervation pattern to the muscles responsible for the occurrence of Co-C is shown in **Figure 6**.

The patient was diagnosed with cranially expanded C5-6 BPI, C4-5-6 avulsion was confirmed during the explorative surgery. The pool of available intraplexal motor donor nerves is shown in **Figure 6**.

In order to reanimate active elbow flexion, NT of ulnar nerve fascicles (m.flexor carpi ulnaris) to the musculocutaneous nerve (branches to biceps brachii muscle) or Oberlin 1 transfer was performed. Two other NTs were performed to reanimate flexion, abduction, and external rotation of the shoulder: Somsak [22, 23] and Bahm [21] NT, respectively.

Physiotherapy was resumed 6 weeks later. 15 mos. after surgery, shoulder flexion (sagittal plane), shoulder abduction (frontal plane), and external rotation were within normal ROM values. BB recovered to M4 and elbow flexion was near 90°, was independent. Hand function was severely impaired by the *induced*

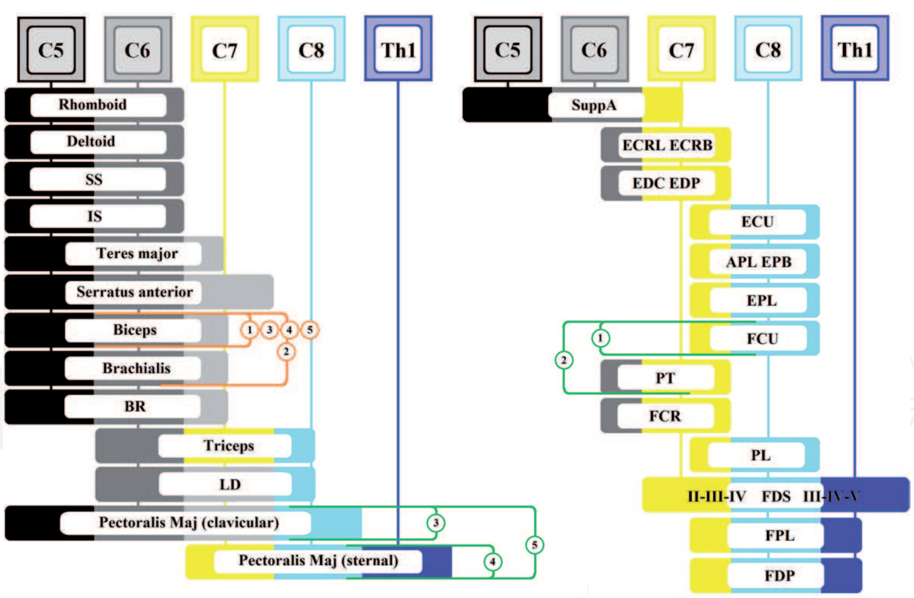

Figure 6.
*The pool of available intraplexal motor donor nerves in clinical example 3. Donor(s) are outlined in green; recipient(s) for the corresponding donornerves are outlined inorange: 1—ulnar nerve fascicles to m. flexor carpi ulnaris; 2—1 + proximal median nerve branch to m. pronator teres (double fascicular NT); 3 and 4—lateral and medial pectoral nerves respectively; 5—both lateral and medial pectoral nerves. *- injured roots are represented in black and gray; **—non-injured roots are represented in color; ***—similar color (thus, roots representation) represents same innervation-pattern of the muscles and is responsible, with great probability, for emergence of co-contraction; SS—suprascapular muscle; IS—infrascapular muscle; BR—brachioradialis; LD—latissimus dorsi muscle; SuppA—supinator antebrachii muscle; ECRL—extensor carpi radialis longus; ECRB—extensor carpi radialis brevis; EDC—extensor digitorum communis; EDP—extensor indicis and digiti minimi; ECU—extensor carpi ulnaris; APL—abductor pollicis brevis; EPB—extensor pollicis brevis; EPL—extensor pollicis longus; FCU—flexor carpi ulnaris; PT—pronator teres muscle; FDS—flexor digitorum superficilalis; FPL—flexor pollicis longus; FDP—flexor digitorum profundus.*

proximal-distal Co-C (FCU/FDP4–5 + FCR-BB) while pulling an object. *Aberrant spontaneous sequential proximal-distal Co-C (TB-WE + FE)* caused extension of the wrist and fingers while reaching the object (**Figure 7**). Wrist stability and the "opening/closing" of the hand were completely lost, the hand became non-functional.

Pathology of biomechanics (**Figure 8**): a "proximal co-contraction pool"—A (Pct and TB) becomes a kind of a 'trigger' for a "distal co-contraction pool"—C (FE and WE), which means that only sequential (in relation to elbow extension maneuver) wrist extension and hand opening is possible—a new "proximal-distal co-contraction pool"—B is formed. The "proximal co-contraction pool" dominates the "distal co-contraction pool" in a direct manner (proximal muscles act first). This type of

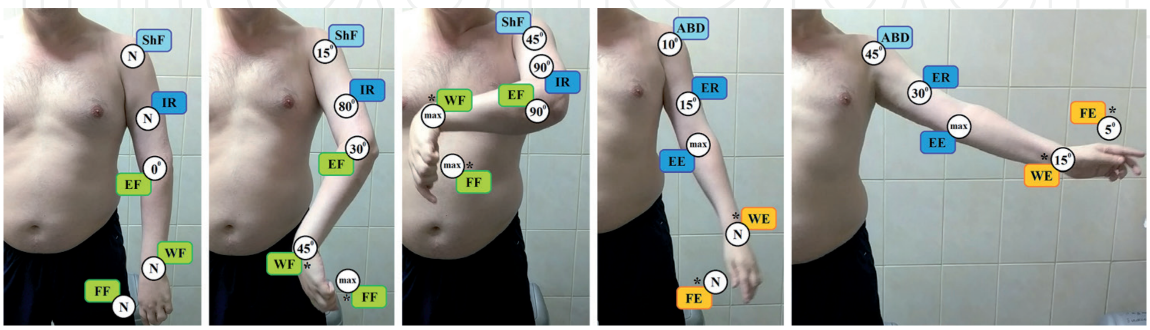

Figure 7.
Correlation between BB function and wrist/finger biomechanics (proximal-distal Co-C during active elbow flexion). ShF—shoulder flexion; ABD—shoulder abduction; IR—shoulder internal rotation; ER—external rotation; EF—elbow flexion; WE—wrist extension; FE—finger extension; N—neutral position; * Induced or regeneration associated proximal-distal Co-C.*

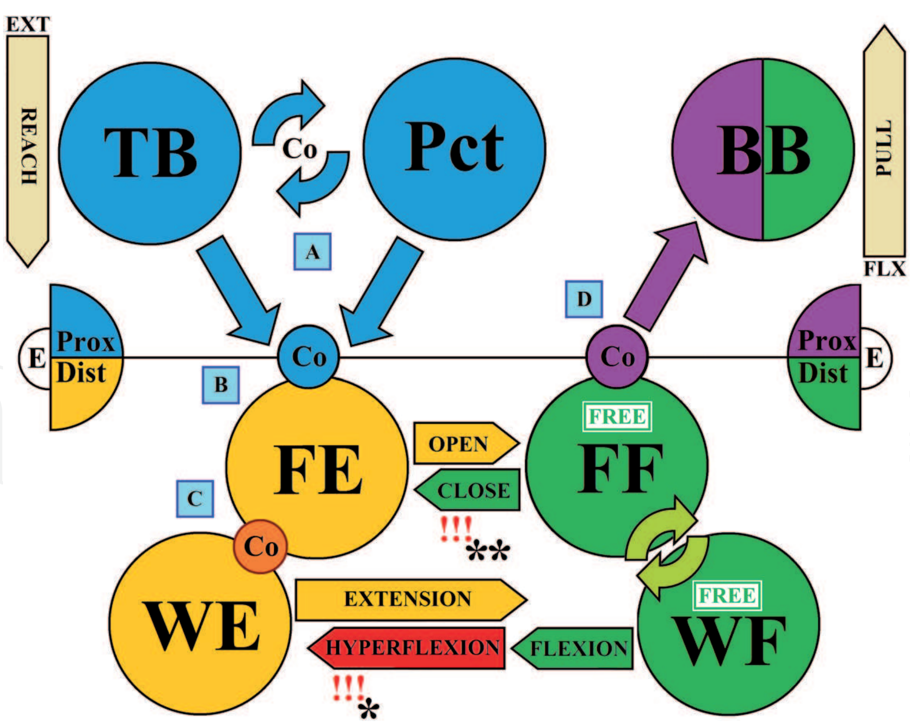

Figure 8.
*Function of proximal and distal segments of the upper extremity in case of BPI with Co-C following Oberlin or double-fascicular NT (hypothesis). EXT—elbow extension, reaching an object; FLX—elbow flexion, pulling an object; TB—triceps brachii muscle; Pct—greater pectoral muscle; BB—biceps brachii muscle; FE—finger extensors; WE—wrist extensors; FF—finger flexors; WF—wrist flexors; A—aberrant spontaneous non-antagonistic proximal-proximal Co-C; B—aberrant spontaneous proximal-distal sequential Co-C (arrow indicates the direction of action of primary Co-C initiator); C—aberrant spontaneous distal-distal sequential Co-C; D—induced proximal-distal Co-C (arrow indicates the direction of action of primary Co-C initiator); E—elbow; blue—primary co-contractors; green—independent movement; both colors—partially independent. *—Aggravation of wrist flexion; **—aggravation of finger flexion.*

co-activation does not disturb the global function in relation to the direction of the entire action of the upper limb reaching an object. Surgical reconstruction of active elbow flexion through Oberlin 1 nerve transfer leads to the emergence of a new form of a "proximal-distal co-contraction pool"—D (FF and BB). Hence, the activation of BB depends on activation of FF (serve as a 'trigger'), the newly emerged co-contraction pool becomes more of a distal-proximal type, where FFs dominate in reverse order (distal muscles act first). This type of co-activation does not disturb the global function in relation to the direction of the entire action of the upper limb pulling an object. As a result, the proximal muscles (above the elbow joint), primary antagonists, BB, and TB can act independently. At the same time, the distal muscles (below the elbow joint), primary antagonists, WE/WF and FE/FF are unable to act independently during basic activities of daily living (ADLs). For instance, reaching the face, mouth, contralateral axillary groove while holding an object (cup, toothbrush, deodorant) requires elbow flexion and at least wrist stability or slight extension. Knowing that the initiator of wrist extension (WE) acts in the opposite direction (TB), their primary function to stabilize the wrist joint is lost, which leads to hyperfunction of FF and WF as initiators of elbow flexion, and finally, to the wrist and finger hyperflexion.

Short rational explanation: Pulling an object when the elbow flexion is done activates the cortical centers of the finger and wrist flexors (Oberlin effect or phenomenon) which leads to wrist and finger hyperflexion. The inability to use the wrist extensors as a compensatory mechanism is related to their activation only when the extremity moves in the opposite direction, the elbow extends when reaching an object.

Conclusion: Induced and *spontaneous proximal-distal and distal-proximal Co-C* are confronting each other, this confrontation disables hand opening/closing during principal basic ADLs. We do not recommend utilizing the Oberlin 1 transfer in similar cases.

This clinical example reflects the *pro* and *contra* arguments of using available fascicles of the ulnar nerve as a donor in case of a-BPI accompanied by aberrant spontaneous proximal-distal Co-C (**Table 2**).

PRO	CONTRA
Oberlin NT could potentially lead to BB recovery with power exceeding M4 and, without confronting function of TB, could possibly produce higher degree of elbow flexion.	Basically, patients without aberrant spontaneous Co-C compensate for the inability to dissociate movements in the proximal and distal segments (the Oberlin phenomenon or effect [8] in almost one-third of cases [6]) with an independent function of wrist extensors, which provides stability and helps to avoid hyperflexion in the wrist joint when reaching (elbow extension) and pulling (elbow flexion) an object. The main contra argument against Oberlin is the occurrence of *induced proximal-distal Co-C (BB and WF/FF)* that severely aggravates on the basis of complete loss of independent wrist extension due to *aberrant spontaneous proximal-distal Co-C (TB and WE/FE).*

Table 2.
Pro and contra arguments of utilizing the ulnar nerve fascicles in case of a-BPI accompanied by aberrant spontaneous proximal-distal Co-C.

3.4 Clinical example 4

A 37-year-old man was admitted to our department 7 mos. after traction-type injury to left brachial plexus in a motorcycle accident; neurological examination revealed non-functioning supraspinatus and infraspinatus muscles, teres major and minor, deltoid and serratus anterior, biceps brachii (BB), coracobrachialis and brachialis muscles (0 points on the MRC scale—M0); latissimus dorsi muscle—M3; greater pectoral (Pct), all heads of triceps brachii (TB) muscles—M4; wrist (WE) and finger (FE) extensors—M4; wrist and finger flexors, intrinsics of the hand—M5. Clinically visible *aberrant spontaneous proximal-proximal non-antagonistic Co-C (Pct-TB)* and *aberrant spontaneous*

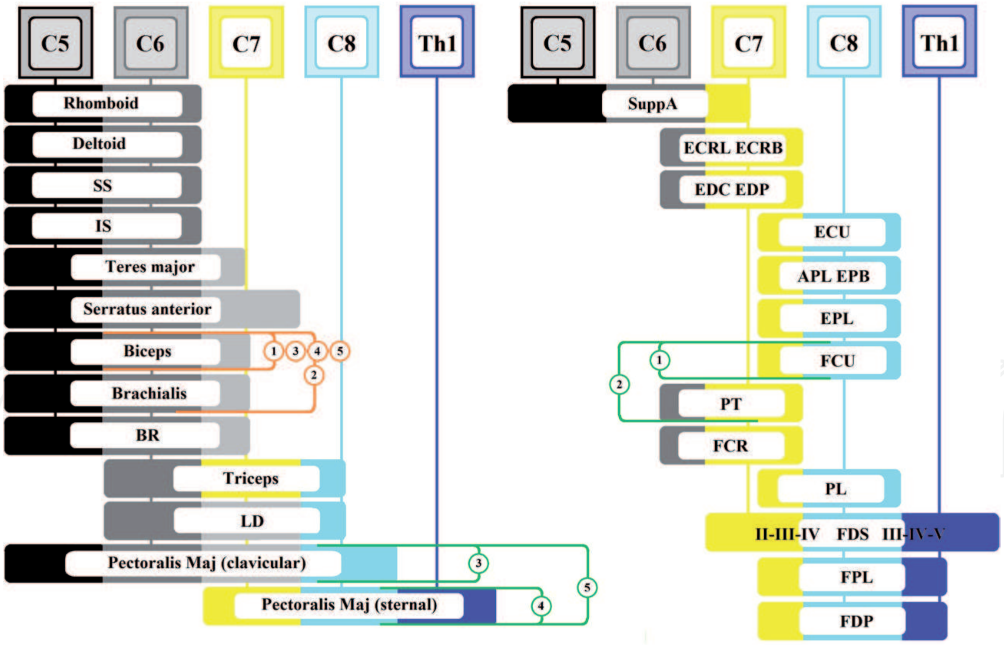

Figure 9.
*Pool of available intraplexal motor donor nerves in clinical example 4. Donor(s) are outlined in green; recipient(s) for the corresponding donor nerves are outlined in orange): 1—ulnar nerve fascicles to m. flexor carpi ulnaris; 2—1 + proximal median nerve branch to m. pronator teres (double fascicular NT); 3 and 4—lateral and medial pectoral nerves, respectively; 5—both lateral and medial pectoral nerves. *—Injured roots are shown in black and gray; **—intact roots are represented in color; ***—a similar color (thus, the representation of roots) represents same innervationpattern of muscles and is most likely responsible for theemergence of co-contraction; SS—suprascapular muscle; IS—infrascapular muscle; BR—brachioradialis; LD—latissimus dorsi muscle; SuppA—supinator antebrachii muscle; ECRL—extensor carpi radialis longus; ECRB—extensor carpi radialis brevis; EDC—extensor digitorum communis; EDP—extensor indicis and digiti minimi; ECU—extensor carpi ulnaris; APL—abductor pollicis brevis; EPB—extensor pollicis brevis; EPL—extensor pollicis longus; FCU—flexor carpi ulnaris; PT—pronator teres muscle; FDS—flexor digitorum superficilalis; FPL—flexor pollicis longus; FDP—flexor digitorum profundus.*

proximal-distal Co-C (TB-WE + FE) were present. The projection of the innervation pattern of the muscles responsible for the occurrence of Co-C is shown in **Figure 9**.

The patient was diagnosed with cranially expanded C5-6 BPI, C4-5-6 avulsion was confirmed during the explorative surgery. The pool of available intraplexal motor donor nerves is shown in **Figure 9**.

In order to reanimate active elbow flexion, there was performed an NT of medial pectoral to musculocutaneous nerve distally to the branches of the coracobrachialis muscle. Two other NTs were performed to reanimate flexion, abduction, and external rotation of the shoulder: Somsak [22, 23] and Bahm [21] NT, respectively.

Physiotherapy was resumed 6 weeks later. 14 mos. after the surgery, abduction of the shoulder in the frontal plane was 75°, external rotation was 20°. BB recovered to M3 and elbow flexion was near 40°. Elbow flexion was severely burdened by the conversion from *aberrant spontaneous proximal-proximal non-antagonistic Co-C (Pct-TB)* to *induced proximal-proximal antagonistic Co-C (BB-TB)*. The clinical picture was dominated by "triceps syndrome".

The injection of botulinum toxin A at the appropriate dose into the long head of the TB was performed. Significant weakening of the long head of the TB was observed 3 mos. after injection. Physiotherapy proceeded and 19 mos. after surgery, the power of BB increased to M4, elbow flexion increased to 90° and BB became partially independent (**Figure 10**). *Aberrant spontaneous proximal-distal Co-C (TB-WE + FE)* remained disturbing and complicated the utilization of the non-dominant upper extremity during daily occupations.

Pathology of biomechanics (**Figure 11**): the pre-surgical "proximal co-contraction pool"—A (Pct and TB) becomes a kind of "trigger" for the "distal co-contraction

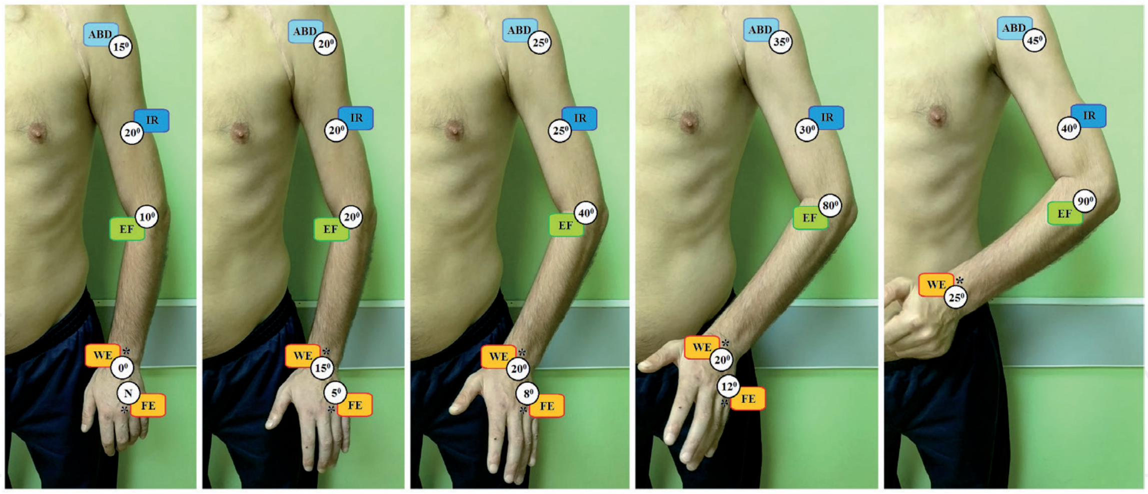

Figure 10.
Correlation between BB function and wrist/finger biomechanics (proximal-distal Co-C during active elbow flexion). ABD—shoulder abduction; IR—shoulder internal rotation; EF—elbow flexion; WE—wrist extension; FE—finger extension; N—neutral position.*

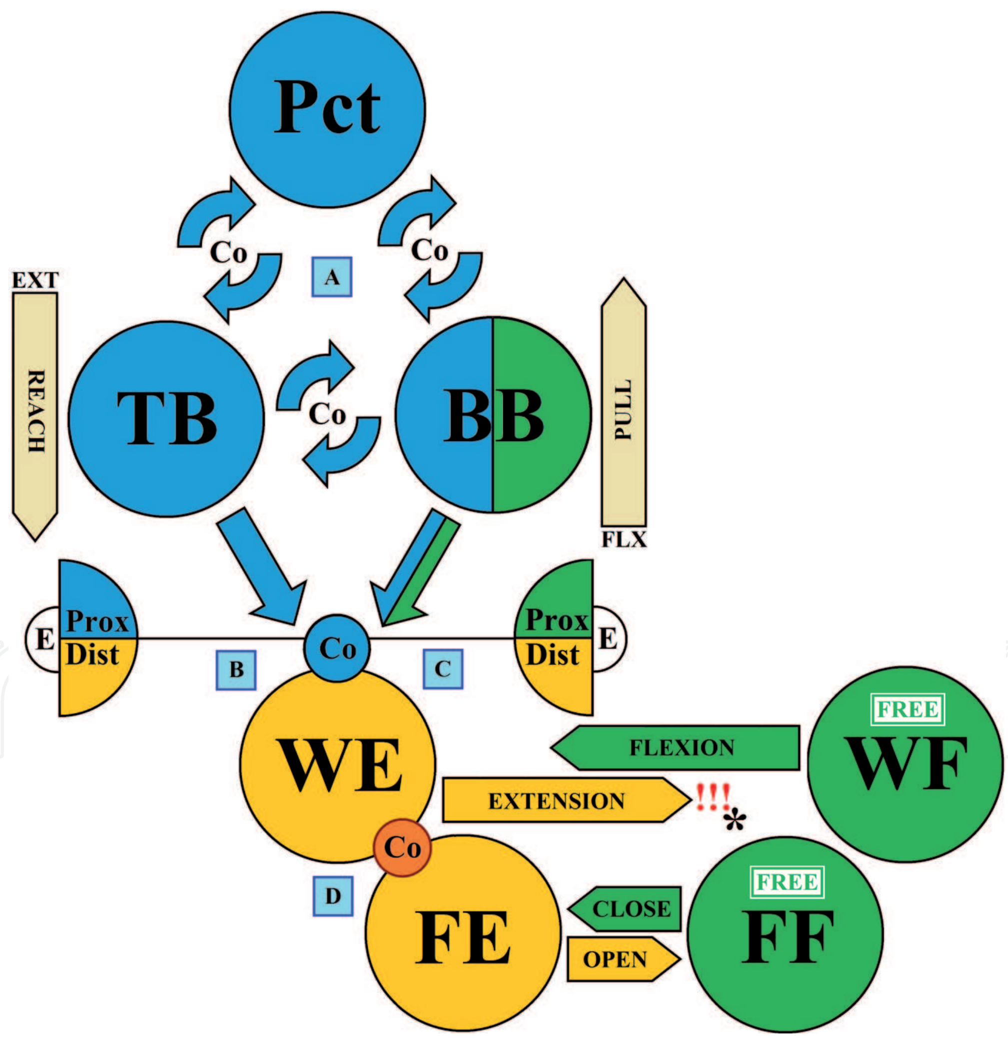

Figure 11.
*Function of proximal and distal segments of the upper extremity in case of BPI with Co-C following medial pectoral to musculocutaneous NT (result). TB—triceps brachii muscle; Pct—greater pectoral muscle; BB—biceps brachii muscle; FE—finger extensors; WE—wrist extensors; FF—finger flexors; WF—wrist flexors; A—aberrant spontaneous non-antagonistic proximal-proximal and induced antagonistic proximal-proximal Co-C; B—aberrant spontaneous proximal-distal sequential Co-C (arrow indicates the direction of action of primary Co-C initiator); C—aberrant spontaneous proximal-distal sequential Co-C associated with elbow flexion (arrow indicates the direction of action of primary Co-C initiator); D—aberrant spontaneous distal-distal sequential Co-C; E—elbow; blue—primary co-contractors; green—independent movement; both colors—partially independent. *—Aggravation of wrist extension.*

pool"—D (FE and WE), which means that only sequential (in relation to the elbow extension maneuver) wrist extension and opening of the hand is possible, a new "proximal-distal co-contraction pool"—B is formed. The "proximal co-contraction pool" dominates the "distal co-contraction pool" in a direct manner (proximal muscles act first). This type of co-activation does not disturb the global function in relation to the direction of the entire upper limb action reaching an object. Surgical reconstruction of active elbow flexion through medial pectoral NT results in the introduction of a new member in the "proximal co-contraction pool" BB. The post-surgical/post-recovery "proximal co-contraction pool"—A—now consists of Pct, TB and BB. As a result, the proximal muscles (above the elbow joint), the primary antagonists, BB and TB could not act independently. Temporary "switching-off" of TB, the primary BB antagonist, leads to partial independence of BB. The "proximal co-contraction pool" still dominates the "distal co-contraction pool" in a direct manner (proximal muscles act first). This type of co-activation does not disturb the global function in relation to the direction of the entire upper limb action both when pulling and reaching an object. The distal muscles (below the elbow joint), the primary antagonist, WE/WF and FE/FF are able to act independently during the basic activities of daily living (ADLs), allowing the hand to open or to close freely. For instance, reaching the face, mouth, and contralateral axillary groove while holding an object (cup, toothbrush, and deodorant) requires elbow flexion and at least wrist stability or minor extension. Knowing that the TB, the initiator of wrist extension (WE), acts simultaneously with BB (both from the same new "co-contraction pool") their primary function of stabilizing the wrist joint is preserved whether during reaching (elbow extension) or pulling (elbow flexion) an object.

Short rational explanation: Pulling an object with the elbow flexion simultaneously activates the cortical centers of the triceps brachii muscle, as well as the wrist and finger extensors. Partial independence of the biceps brachii muscle is most probably related to the "drifting" of the cortical center of the elbow flexion. The inability to completely dissociate the muscles of the "proximal co-contraction pool" (TB, BB, B) is reflected in the power and angular performance rate of the biceps brachii muscle. The co-existence of confronting *proximal Co-C* upon reaching and pulling an object with elbow flexion/extension has only a minor influence on wrist flexion/extension, hand opening/closing, while the preexisting *proximal-distal Co-C* enables physiologic wrist positioning during ADLs.

Conclusion: Regardless of the fact that we obtained only 90° of the elbow flexion with medial pectoral NT and the confronting function of TB partially disabled independent elbow flexion, the distal segments of the upper extremity remained highly functional.

This clinical example reflects the *pro* and *contra* arguments of the utilization of an available medial pectoral donor nerve in case of BPI accompanied by aberrant spontaneous proximal-distal Co-C (**Table 3**).

PRO	CONTRA
The conversion of *aberrant spontaneous non-antagonistic proximal-proximal Co-C (Pct-TB) into induced antagonistic proximal-proximal Co-C (BB-TB)* did not produce confronting Co-Cs during reaching and pulling an object only in the distal segments of the upper extremity. As a result, the main pro argument in favor of the provided NT is that it does not disturb the independent hand opening. Wrist hyperextension that accompanies either reaching or pulling an object is compensated for the independent function of the wrist flexors.	The conversion of the *aberrant spontaneous non-antagonistic proximal-proximal Co-C (Pct-TB) into induced antagonistic proximal-proximal Co-C (BB-TB)* produces confronting Co-Cs during reaching and pulling an object in the proximal segment of the upper extremity. As a result, BB becomes partially independent of TB, yet the confronting. Co-C between TB and BB prevents BB from executing its full flexion potential in the elbow joint. Regardless the fact that BB power reaches M4, the elbow flexion does not exceed 90°

Table 3.
Pro and contra arguments of utilization of the medial pectoral nerve in case of a-BPI accompanied by aberrant spontaneous proximal-distal Co-C.

4. Summary

We believe that, regardless of all existing limitations, we provide an interesting insight in terms of a compromise solution for a specific case of BPI accompanied by Co-Cs of different types. The study of the natural history of the individual regeneration process, a thorough preoperative evaluation of *pros* and *contras*, and advantages and disadvantages of available NTs, lead to the emergence of a reconstruction plan that allows not only to expand the functions of the upper arm (restore elbow flexion), but also not to disturb the pre-existing partially pathological, yet highly functional, biomechanics of wrist and fingers, to improve the overall function of the entire upper extremity.

Author details

Alexander A. Gatskiy* and Ihor B. Tretyak
The State Institution “Romodanov Neurosurgery Institute of National Academy of Medical Sciences of Ukraine”, Kyiv, Ukraine

*Address all correspondence to: drgatskiy@outlook.com

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