Review

An electroencephalography-based human-machine interface combined with contralateral C7 transfer in the treatment of brachial plexus injury

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Abstract

Transferring the contralateral C7 nerve root to the median or radial nerve has become an important means of repairing brachial plexus nerve injury. However, outcomes have been disappointing. Electroencephalography (EEG)-based human-machine interfaces have achieved promising results in promoting neurological recovery by controlling a distal exoskeleton to perform functional limb exercises early after nerve injury, which maintains target muscle activity and promotes the neurological rehabilitation effect. This review summarizes the progress of research in EEG-based human-machine interface combined with contralateral C7 transfer repair of brachial plexus nerve injury. Nerve transfer may result in loss of nerve function in the donor area, so only nerves with minimal impact on the donor area, such as the C7 nerve, should be selected as the donor. Single tendon transfer does not fully restore optimal joint function, so multiple functions often need to be reestablished simultaneously. Compared with traditional manual rehabilitation, EEG-based human-machine interfaces have the potential to maximize patient initiative and promote nerve regeneration and cortical remodeling, which facilitates neurological recovery. In the early stages of brachial plexus injury treatment, the use of an EEG-based human-machine interface combined with contralateral C7 transfer can facilitate postoperative neurological recovery by making full use of the brain's computational capabilities and actively controlling functional exercise with the aid of external machinery. It can also prevent disuse atrophy of muscles and target organs and maintain neuromuscular junction effectiveness. Promoting cortical remodeling is also particularly important for neurological recovery after contralateral C7 transfer. Future studies are needed to investigate the mechanism by which early movement delays neuromuscular junction damage and promotes cortical remodeling. Understanding this mechanism should help guide the development of neurological rehabilitation strategies for patients with brachial plexus injury.

Key Words: arm injuries; brachial plexus; brain-computer interfaces; nerve transfer; nerve regeneration; nerve tissue; neurofeedback; neurological rehabilitation; user-computer interface

Introduction

Traumatic brachial plexus injury (BPI) is a common nerve injury caused mainly by reverse movement of the head, neck, and shoulder. The brachial plexus can also be damaged by surgery or radiation (Yan et al., 2019). BPI is a severe and devastating condition that is observed in up to 4.2% of all multi-trauma patients, usually affects young adults, and has significant socioeconomic implications (Yan et al., 2019; Estrella et al., 2021). Severe BPI, particularly total nerve root avulsion, can lead to partial or complete loss of upper limb function and has poor prognosis. Early nerve repair is essential for functional recovery. Existing repair methods of BPI include nerve repair, nerve grafting, and nerve transfer (Colbert and Mackinnon, 2008; Wehrli et al., 2011; Miller et al., 2021). Other compensatory treatments, such as muscle and tendon transplantation, attempt to restore motor function of the upper limb. Although these repair methods can achieve promising results, motor function is usually not completely restored. Even after successful surgical reconnection of injured peripheral nerves and treatment with different growth factors, satisfactory neurological recovery may not occur (Rocco et al., 2018; Yi et al., 2019).

Peripheral nerve regeneration after BPI is challenging in clinical practice for several reasons (Rui et al., 2018). Because BPI is a proximal nerve injury, it takes a long time for the regenerating nerve to grow and innervate the distal effector. During this extended period, the distal effector can atrophy, which greatly reduces the likelihood of functional recovery (Kemp et al., 2010). In addition, cortical plasticity is a critical factor that affects the success of repair after peripheral nerve injury (PNI) (Wang et al., 2010; Facchini et al., 2021). If the reentrant nerve plays a dominant role, it must form an effective reconnection in the cortex (Sturma et al., 2018; Hou et al., 2020). Therefore, satisfactory peripheral nerve regeneration and cortical remodeling are only possible over the long term.

Since 2013, researchers have been applying electroencephalography (EEG) signal-based upper limb control devices to assist with movement, as shown in **Table 1**. The primary purpose of the brain-computer interface is to accurately identify and extract EEG signals that control limb movement. The signals are translated and amplified by the computer and then transmitted across the PNI site to a robotic arm exoskeleton or distal electrical stimulation device. Unlike existing purely mechanically driven rehabilitation devices, EEG-based devices can actively control distal limb movement to maintain target muscle activity. Early functional exercise not only promotes peripheral nerve rehabilitation, but also accelerates cerebral cortical remodeling. At the same time, it retransmits peripheral feedback signals, which optimizes the mechanical response to maximize the rehabilitation effect. The timeline of studies of EEG-based human-machine interface combined with contralateral C7 transfer for the treatment of BPI is shown in **Figure 1**.

This review summarizes the application of C7 nerve transfer in treating ipsilateral BPI, discusses the possible mechanism by which the brain-computer interface promotes BPI rehabilitation, and proposes a viable procedure for brachial plexus repair that promotes functional recovery.

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Table 1 | **A summary of electroencephalography (EEG) signal-based prosthesis in patients with functional limb loss**

Authors	Electrode counts (*n*)	Features	Task	Application significance
Robinson et al., 2013	128	Regularized wavelet-common spatial pattern algorithm	Hand movement	High precision controllable hand-assisted mobility device
Yi et al., 2013	64	Multi-class CSP; multi-class stationary Tikhonov regularized CSP; multi-class CSP based on generalized eigenvector	Limb action	Medium-precision controllable upper limb mobility device
Woo et al., 2015	64	CSP algorithm	Arm movements	Medium-precision controllable upper limb mobility device
Jochumsen et al., 2016	25	Temporal features and spectral features and their combinations	Hand grasping	Low-precision controllable hand mobility device
Roy et al., 2017	29	Autoregressive parameter, Hjorth parameter, correlation dimension, Hurst's exponent	Decoding different grasp types	Low precision controlled upper limb mobility device
Iturrate et al., 2018	64	Temporal and spectral domains	R-G actions & variable force	Medium precision upper limb strengthening device
Roy et al., 2018	29	Correlation dimension in different bands	Grasp patterns	Low-precision controlled upper limb mobility device
Schwarz et al., 2018	61	Low-frequency time domain features from 0.3 to 3 Hz	Reach to grasp actions	Medium-precision prosthetic devices

CSP: Common spatial patterns.

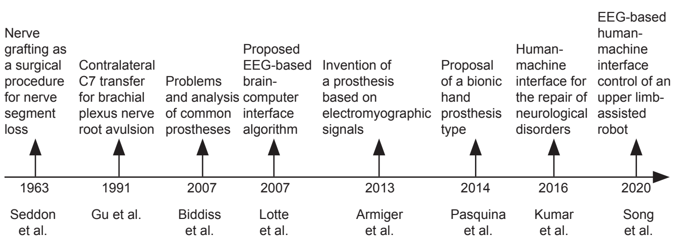

Figure 1 | **Timeline of studies of electroencephalography-based human-machine interface combined with contralateral C7 transfer for the treatment of brachial plexus injury.**

Search Strategy

This manuscript systematically reviews the rodent, non-human primate, and human studies of nerve transfer treatment of BPI that have been published between 1990 and 2021. The PubMed and EMBASE databases were searched using the following key words: "brachial plexus injury", "C7 nerve transfer", and "peripheral nerve regeneration". The articles generated by the search were further screened based on titles and summaries. The databases were also searched for studies of brain-computer interface use in nerve injury repair using the following key words: "arm injuries", "brachial plexus", "brain-computer interface", "nerve transfer", "nerve regeneration", "nerve tissue", "neurofeedback", "neurological rehabilitation", and "user-computer interface".

Brachial Plexus Injury

Brachial plexus injury treatment

BPI can cause loss of shoulder elevation, abduction, and rotation; elbow flexion and extension; and wrist and finger flexion and extension (Sulaiman et al., 2009; Schessler and McClellan, 2010). As **Figure 2** shows, BPI can be classified according to the portion of the arm predominantly affected: upper arm (C5–C6 with or without C7 injury), lower arm (C8–T1 injury), and whole arm (C5–T1 injury). Injury treatment mainly consists of surgery, including nerve repair, nerve grafting, nerve transfer, and functional free muscle transplantation to replace original muscle function (Dubuisson and Kline, 2002; Muhetidier et al., 2011).

Direct suturing of the adventitia/intima is the most common method of nerve repair and is mainly suited for acute localized injury. The proximal and distal nerve stumps can be directly sutured in tension-free injuries, which include sharp nerve transection and penetrating injury. Nerve transplantation can be used when the nerve defect is too large for tension-free direct suturing. The sural nerve is commonly harvested to use for grafting; other options include the medial brachial cutaneous nerve or the medial forearm cutaneous nerve. Although these donor nerves do not have a sufficient number of medullary nerve fibers to repair multiple thicker nerves (Garg et al., 2011; Davidge et al., 2021; Hill et al., 2021; Macêdo et al., 2021; Rasulić et al., 2021), nerve transplantation avoids the need for donor region cortical remodeling and provides a sufficient number of motor bundles. However, nerve donor area damage is inevitable, and it cannot fundamentally solve the problems of neuromuscular dysfunction and muscle atrophy.

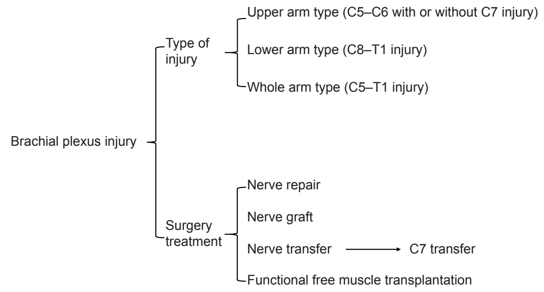

Figure 2 | **Types of brachial plexus injury and treatment.**

Functional muscle and tendon transplantation can also partially restore injured limb function. The trapezius muscle is usually preserved in BPI patients and can be transferred to repair the shoulder. Although the superior trapezius muscle has been used to repair shoulder abduction function, results have been mixed (Terzis and Kostopoulos, 2007; Elhassan et al., 2009). As the function of the infraspinatus muscle is closely related to that of shoulder abduction, the repair method in which the infraspinatus muscle is used as the donor has a success rate of greater than 90% (Elhassan, 2014). However, shoulder abduction and rotation require action of multiple muscles (Elhassan et al., 2012) and single tendon transfer cannot completely restore function; therefore, it is often necessary to rebuild multiple functions. Moreover, the outcome of muscle and tendon transplantation is often not ideal and therefore is generally used when neurosurgery has failed or the patient suffers from forearm and hand motor function limitation.

C7 transfer

The concept of nerve transfer as a nerve injury treatment was introduced in the 1950s. With advances in knowledge and surgical technology, it has become a preferred method for BPI treatment (Feng et al., 2019; Fasce et al., 2021). The spinal accessory, phrenic, suprascapular, axillary, and intercostal nerves as well as the contralateral C7 nerve root may all be used as the donor for nerve transfer (Midha, 2004; Addas and Midha, 2009). A summary of contralateral C7 transfer for various injuries is shown in **Table 2**. Because isolated C7 nerve root transection does not lead to obvious motor and sensory defects, Gu et al. (1992) proposed using the contralateral C7 nerve root as the donor in repair of traumatic brachial plexus avulsion injury. Anatomically, the muscles innervated by C7 are also usually innervated by C6; C8, C5, and T1 may also play a partial role (Li et al., 2017; Liu et al., 2018). In addition, the C7 nerve root contains more myelinated nerve fibers than other donor nerves, which can provide sufficient power for the transplantation area (Alawieh et al., 2021). In summary, nerve transfer has become a widely used and often successful method to treat BPI. However, surgical repair of complex brachial plexus defects cannot resolve the problems of neuromuscular junction dysfunction and target muscle atrophy.

Realization of Human-Machine Interfaces

Types of human-machine interfaces

The invasive human-machine interface includes skeletal muscle implantation and peripheral nerve implantation (Navarro et al., 2005; Christensen et al., 2014; Gelenitis et al., 2021; Hejazi et al., 2021). As shown in **Figure 3A** and **B**, the peripheral nerve-implanted electrode and muscle-implanted electrode can collect the local electrical nerve signals of the corresponding area with high precision. This human-machine interface mainly relies on an invasive guide needle or electrode to obtain signals from skeletal, muscle, or peripheral nerves. Its advantage lies in the stability and high intensity of the signal sources. However, the trauma induced by the needle or electrode limits its clinical application. Although some invasive electrodes are designed to promote peripheral nerve growth, regenerative electrodes can only be used in transected peripheral nerves. Regenerated axons grow slowly through the channel; therefore, the effect cannot be quickly verified by experiments. While it is feasible to use regenerative electrodes to stimulate a small number of regenerated fibers (Spearman et al., 2020), there is no practical way to achieve complete nerve regeneration. The signal source of the non-invasive human-machine interface mainly comes from EEG and electromyography (EMG) (Kuiken et al., 2007; Marchal-Crespo and Reinkensmeyer, 2009).

As shown in **Figure 3C** and **D**, the EEG and EMG signals of a non-invasive interface are not determined as accurately as invasive electrode signals. Moreover, they are also difficult to distinguish from confounding signals

Table 2 | **A summary of contralateral C7 transfer for median, musculocutaneous and radial/triceps nerve injuries**

Recipient nerve	Authors	Number	Injury type	Great motor recovery	Great sensory recovery	Application significance
Median nerve	Gu et al., 1992	4	Total BPAI	2	3	The earliest report
	Ei-Gammal et al., 2002	7	Total BPAI	NA	NA	Least effective coverage
	Chen et al., 2007	3	Total BPAI	3	3	Best results reported
	Muhetidier et al., 2011	16	Total BPAI	3	11	Improved transplant effect
	Tu et al., 2014	40	Total BPAI	5	21	Improved transplant effect
Musculocutaneous nerve	Gu et al., 1992	3	Total BPAI	2	NA	The earliest report
	Hierner et al., 2007	6	Total BPAI	1	NA	Least effective coverage
	Chuang et al., 2012	23	NA	19	NA	Best results reported
	Wang et al., 2013	47	Total BPAI	28	NA	Improved transplant effect
Radial Nerve	Gu et al., 1992	2	Total BPAI	1	NA	The earliest report
	Hattori et al., 2005	1	Total BPI	0	NA	Least effective coverage
	Terzis et al., 2009	10	NA	2	NA	Improved transplant effect
	Muhetidier et al., 2011	2	Total BPAI	0	NA	Least effective coverage
Triceps nerve	Terzis et al., 2009	21	NA	7	NA	The earliest report
	Terzis et al., 2012	20	NA	5	NA	Improved transplant effect
	Gao et al., 2013	10	Total BPAI	0	NA	Least effective coverage

BPAI: Brachial plexus avulsion injury; NA: not available.

arising from surrounding tissues. Through a series of complex signal processors, functional control signals are extracted, and external flexible exoskeletons or unique robotic arms are directed to assist patients in active recovery. The use of a non-invasive human-machine interface allows complete avoidance of surgical risks. A previous study has shown that a brain-computer interface can perform delicate tasks such as text creation (Marshall and Farah, 2021). Warwick et al. (2003) implanted multielectrode arrays in a healthy subject and achieved bidirectional transmission between the experimental robot arm and the peripheral nervous system. These works have opened many research opportunities in the fields of human-machine interface and activity monitoring (Xiao and Menon, 2019). The signals acquired by the brain-computer interface originate from the cerebral cortex, which is characterized by a complex signal. However, multi-channel high-density electrodes are now available that can accurately acquire signals from different distribution points within a specific area and differentiate and integrate them to obtain the desired signal band. After decoding by a computer, a similar effect to that of an invasive human-machine interface can be achieved. Therefore, compared with an invasive human-machine interface, the non-invasive EEG-based interface ensures recognition accuracy, reduces unnecessary trauma, and has better application prospects in promoting nerve injury rehabilitation.

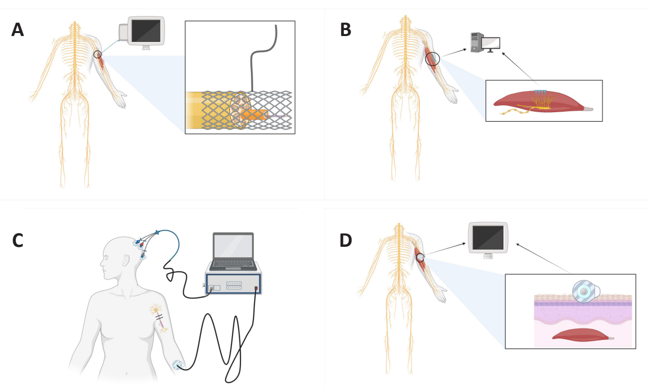

Figure 3 | **Types of human-machine interface.**
(A) Peripheral nerve-implanted electrode. Black line: electric wire; black circle: peripheral nerve injury site; (B) Muscle-implanted electrode. Black circle: peripheral nerve injury site; (C) EEG human-machine interface. Black line: electric wire; (D) EMG human-machine interface. Black circle: Peripheral nerve injury site; black box: magnified view of local damage.

EEG human-computer interface

Human-machine collaboration helps to improve the recognition of human motion signals. The two main types of non-invasive electrical signals used to recognize movement intention are EEG and EMG (Leeb et al., 2011; Cui et al., 2017). The use of EEG signals allows for faster detection of motor intent than EMG (Haufe et al., 2011). In human-machine collaborative systems, early decoding of human movement intentions allows for better execution of assigned tasks. Considerable research has been conducted regarding brain-computer interface systems over the last few decades. For example, in 1988, Farwell and Donchin (1988) developed an EEG control system with selectable letters. Wolpawant et al. (1991) first investigated an EEG-based computer cursor controller. Edelman et al. (2019) used EEG signals to achieve neural control of robotic devices. Decoding motor parameters directly from EEG signals provides intuitive and natural control compared with brain-computer interfaces based on motor images or visual evoked potentials (Ofner et al., 2019).

Application of a human-machine interface based on EEG

The human-machine interface based on EEG does not directly promote nerve regeneration to achieve improved function. Rather, it connects to a flexible exoskeleton or mechanical arm through the organic coupling of nerves and an electronic system with the help of an external environment to achieve average or superior rehabilitation effects. Several studies have demonstrated the effect of the mechanical exoskeleton on functional rehabilitation. Lo et al. (2010) showed that mechanical exoskeleton adjuvant therapy could be used to achieve better function and task completion ability than conventional treatment and demonstrated how human-machine auxiliary therapy improves the therapeutic effects of traditional therapy. Because of progress in this technology, development of the human-machine interface has gradually moved in the direction of bilateral transmission. With bilateral transmission, the interface can accurately control exoskeleton function by receiving electrical signals from the center and feeding back motor information that prompts the central nervous system to feel the presence of limbs. This feedback system is shown in **Figure 4**.

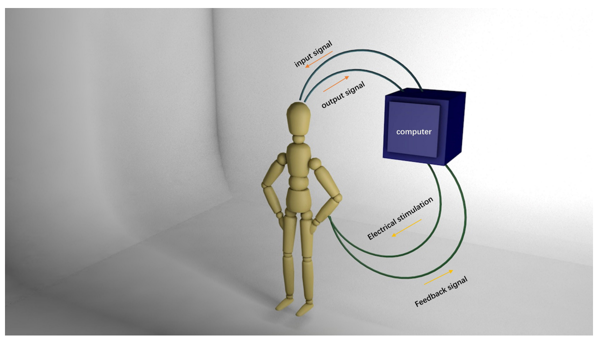

Figure 4 | **Schematic diagram of an electroencephalography-based human-machine interface.**
The computer obtains an electrical signal from the cerebral cortex and directly transmits this signal downward to the distal end of the injury with a certain intensity of electrical stimulation. At the same time, the feedback signal is collected and processed by the computer and transmitted back to the cerebral cortex.

The output of EEG signals can be used to control the movement of prosthetics, orthoses, wheelchairs, robots, and computer mice (Hochberg et al., 2012; Gilja et al., 2015; Jarosiewicz et al., 2015). This signal output can also act directly on muscle in the form of electrical stimulation (Pfurtscheller et al., 2003). The brain response can be fed back as visual (Hochberg et al., 2006; Caria et al., 2012), auditory (Nijboer et al., 2008; Leeb and Pérez-Marcos, 2020), or haptic stimuli that vary according to the measured brain activities (Chatterjee et al., 2007; Lugo et al., 2014). Information about limb position or movement can be used to monitor physical activities or for applications of the human-machine interface (Xiao and Menon, 2019). In addition, a human-machine interface has been used for receiving and translating neural electrical signals in amputation patients to assist with movement (Ortiz-Catalan et al., 2014; Raspopovic et al., 2014; Tan et al., 2014; Oddo et al., 2016; Valle et al., 2018; Petrini et al., 2019) and to feed back touch and proprioceptive sensations from the exoskeleton to the center (Raspopovic et al., 2014; Oddo et al., 2016). Compared with an EMG-based human-machine interface, an EEG-based interface can make full use of the human brain's computing power without the need for complicated judgment instructions through an external calculator. Such an interface can execute the brain's motor instructions and transmit feedback signals back to the brain to allow completion of more complex and precise activities. Furthermore, it can receive slow cortical potentials (Kübler et al., 2001), sensorimotor rhythms, P300 event-related potentials (Kübler et al., 2009; Halder et al., 2010), steady-state visual evoked potentials (Lesenfants et al., 2014), and error-related negative evoked potentials (Chavarriaga and Millan Jdel, 2010). To reduce muscle atrophy and maintain muscle function as much as possible, intervention should be performed in the early stage of injury. The influence of the human-machine interface on motor learning offers exciting new prospects for retraining skills after neural injury.

Numerous Mechanisms for Repairing Brachial Plexus Injury

Remodeling skeletal muscle structure and muscle fiber types

The mechanism of brachial plexus nerve injury repair is shown in **Figure 5**. Most included studies have shown that denervated muscle mainly manifests as a decrease in wet muscle weight. Reduction in muscle cross-sectional area results from a decline in muscle fiber diameter, loss of cellular nuclei, and cellular apoptosis (Gwam et al., 2021). After treadmill training, the level of IGF-1 protein in muscle cells increases, suggesting that satellite cell activity increased and promoted muscle fiber production (Stevens-Lapsley et al., 2010; Ahuja et al., 2021; Chen et al., 2021). Simultaneously, motor endplates play a vital role in motor function change. Several studies have shown that quantity and quality of motor endplates can significantly improve as a result of long-term exercise. Therefore, the human-machine interface promotes muscle fiber formation and motor endplate maintenance through the early application of exercise training following injury.

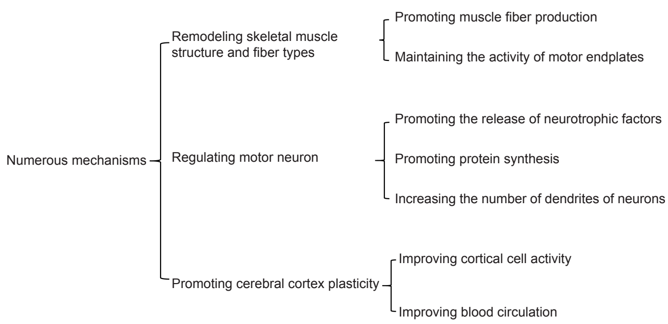

Figure 5 | Mechanisms of brachial plexus injury repair.

Motor neuron regulation

After PNI, the speed and number of regenerated axons are disturbed, mainly by neurotrophic factors. Exercise is effective for functional recovery after spinal cord injury in rodents and cats (Alluin et al., 2011), which may be related to neurotrophic factors induced by exercise. Both motor neuron nucleolar area and rate of protein synthesis increase in rats that undergo treadmill training (Kang et al., 1995; Boeltz et al., 2013). Neuronal anterograde and retrograde transport of axonal proteins also increases, which promotes an increase in dendrites (Shin et al., 2014). This positive promoting effect may be realized through the human-machine interface.

Promoting cerebral cortex plasticity

Changes in the cerebral cortex occur after PNI. As nerves regenerate and axons regrow into target organs, the afferent nerves can gradually transmit signals to the center. Afferent stimulation can improve cortical cell activity and induce cerebral cortex reorganization (Hickmott and Merzenich, 2002). As shown in **Figure 6**, cerebral cortex remodeling after PNI repair can be promoted via the human-computer interface. Mice experiments have shown increased spontaneous neuron generation in the corresponding region of the forelimb cortex after hindlimb PNI, indicating that hindlimb nerve amputation caused cortical remodeling (Kao et al., 2011). Jurkiewicz et al. (2007) found that the degree of functional rehabilitation after functional exercise is related to the degree of cortical activation as measured using fMRI. Bicycle training following repair in a rabbit spinal cord injury model can increase the complexity and density of dendritic spines in the dentate gyrus, which indicates that exercise training can promote axonal regeneration and structural remodeling of the cerebral cortex. In addition, exercise training can affect brain remodeling by improving blood circulation and the status of some neurosecretory factors. Animal PNI studies have shown that plasticity-related neurotrophic factor, adenylate cyclase type 1 (ADCY1), and brain-derived neurotrophic factor secretion are remarkably higher in exercising animals than those that do not exercise. These factors are essential for axonal regeneration and establishment of synapses. Exercise can promote the remodeling of cortical neurons (Graziano et al., 2013). Other studies have shown that exercise stimulates the proliferation of neural endogenous stem cells, which can secrete brain-derived neurotrophic factor, a factor that regulates neural plasticity and can improve motor function.

Brachial plexus repair by nerve transfer can provide sufficient motor and sensory fibers to the affected brachial plexus while minimizing impact on the donor area. However, the site of nerve repair is distant from the target muscle. As the nerve regenerates, the target muscle atrophies and becomes nonfunctional, and it is thus difficult for the regenerated nerve to form an effective neuromuscular junction to complete the connection (Ali et al., 2019; Wang et al., 2019; Yin et al., 2019; Gupta et al., 2020; Mole et al., 2020). In contrast, the brain-computer interface can promote peripheral muscle activity in the early stage of injury, slow down neuromuscular junction atrophy, and maintain target muscle activity. Simultaneously, the feedback signal benefits the newly developed nerve in terms of remodeling of the cortex and corresponding brain regions (Alvarez et al., 2010). Studies have shown that the precise control of cortical remodeling may be an important factor in repairing PNI and achieving better rehabilitation results. As illustrated in **Figure 7**, the human-machine interface can help BPI patients achieve better functional outcome by promoting skeletal muscle fiber regeneration, regulating motor neurons, and promoting cerebral cortex plasticity. In summary, applying an EEG-based human-machine interface in BPI patients may improve the surgical outcome of nerve transfer.

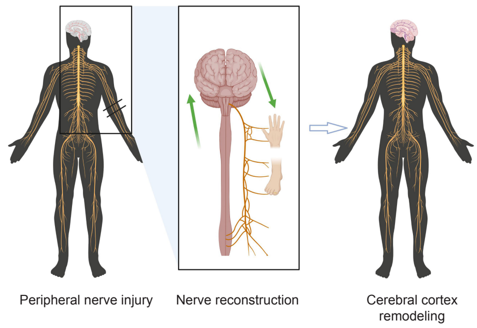

Figure 6 | Central remodeling of the cerebral cortex caused by peripheral nerve reconnection.
After the peripheral nerves regenerate and connect, the cerebral cortex that controls the corresponding area undergoes rapid remodeling and forms effective functional control. Black double horizontal line: point of nerve damage; green double arrows: neural signaling and cortical remodeling; black circle: peripheral nerve injury site.

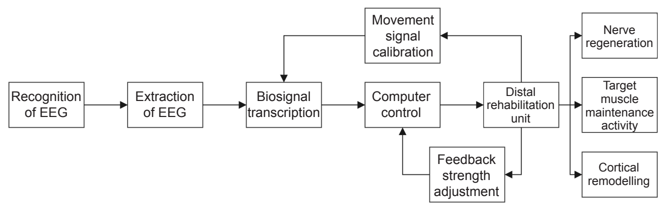

Figure 7 | Flowchart for neurological rehabilitation after peripheral nerve injury using an electroencephalography-based human-machine interface.

Conclusions and Future Prospects

Human neural activity is used as input control in human-machine interfaces. Previous studies have demonstrated the advantages of EEG-based interfaces, which are the most common brain-machine interface used today. Song et al. (2020) proposed an EEG-based human-machine interface to enable paralyzed patients to control an assistive robot. EEG can not only identify working signals, but can also distinguish subtle emotional signals (López-Hernández et al., 2019). Assistive robots can help users with motor actions and provide an exploration of broader applications of human-robot interaction. However, integration of an EEG-based human-machine interface with rehabilitation of surgically repaired PNIs has not yet been addressed despite the need for methods to improve rehabilitation outcomes.

Limitations and advantages

Development of an effective human-machine interface for PNI rehabilitation requires in-depth cross-disciplinary collaboration between science, engineering, and medicine. The multi-dimensional combined approach proposed in this study has not yet been implemented in the clinic, and the development and approval cycle for a rehabilitation system can be long. However, brain-computer interface-based prosthetics are a reality and have great potential to improve rehabilitation outcomes after C7 nerve transfer for severe BPI.

Several points deserve particular attention. Future work and reliable replication of previous studies are required to ensure that EEG can be assimilated in automated human-machine interfaces. In addition, engineering quality is equally important. Most existing external brain-machine interface-controlled exoskeleton devices are only in the laboratory stage; eventually, they must be durable enough to allow long-term clinical use. Accuracy of dynamic recognition of EEG signals is another major factor that limits the stable provision of services. The rates of correct recognition by existing algorithms range between 40.5% and 92.7% in previous reports, which should be improved. New density sensors show great potential for use in human-machine interfaces, such as the latest high-density EEG collectors, which have extremely high resolution and the ability to acquire multi-conductor electrical signals in specified areas. Such collectors should provide a basis for precise acquisition and control of human-machine interfaces. In the early stages of rehabilitation after C7 nerve transfer for BPI, full use of the brain's computing power and active control of external mechanical aids for functional exercise can greatly contribute to better outcomes. In the long term, it can prevent disuse atrophy of muscles and target organs and maintain neuromuscular junction effectiveness. Cortical remodeling also becomes important for recovery as the brain re-establishes effective pathways.

Innovation and comments

This review advocates integrating a human-machine interface into the rehabilitation process after PNI repair and argues for a recovery that does not rely solely on surgery to heal massive injuries. Active, controlled, and safe functional exercise at a later stage is equally important. The unique feedback coordination mechanism of the human-machine interface further enhances controllability of the rehabilitation process. In contrast to conventional manual rehabilitation, the interface has potential to maximize user initiative, regenerate peripheral nerves, and promote cortical remodeling for better and faster recovery.

Conclusion and prospects

The method proposed in this study suggests a possible direction for the future development of human-machine interfaces, as well as a feasible solution to BPI, a difficult clinical problem. In the future, the application of artificial intelligence technology in the field of human-machine interface will make it possible to achieve excellent rehabilitation results with BPI.

Although remarkable progress has been made in BPI repair, in the future, human-machine interfaces will also play a critical role in recovery from nerve injury. The mechanism by which early exercise delays the disintegration of the injured neuromuscular junction and promotes cortical remodeling requires further investigation. Elucidating this mechanism may provide new ideas for functional rehabilitation after nerve injury. Combining various therapeutic methods (new materials, nerve growth factors, electrical stimulation) with C7 nerve transfer may enhance recovery after BPI. An EEG-based human-machine interface shows excellent potential to improve surgical outcomes after brachial plexus repair.

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Conflicts of interest: *The authors declare that there are no conflicts of interest associated with this manuscript.*

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