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REVIEW

Progress in the Application of Brain-Computer Interface Technology to Rehabilitation Treatment and Nursing in Patients With Stroke

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Abstract

From the perspective of the nursing discipline, this paper examines the current status, influencing factors, challenges, countermeasures and practical evolution of brain-computer interface (BCI) application in stroke rehabilitation. BCI has been extended to multiple rehabilitation scenarios, including motor function reconstruction, cognitive intervention, consciousness assessment and communication assistance. Its clinical integration is driving profound changes in nursing practice at three levels: nursing assessment extends from behavioural observation to neural signal interpretation; nursing decision-making advances from executing medical orders to collaborative prescribing; and nursing humanism evolves from bedside companionship to a new form of technology-humanism integration. In this process nurses' roles are expanding to technical coordinators, rehabilitation promoters and interdisciplinary communication hubs. Technical instability, individual variability, gaps in nursing knowledge and skills, and lagging ethical guidelines still constrain clinical translation, however. The nursing discipline therefore needs to build proactively an interdisciplinary knowledge system integrating neuroscience, rehabilitation therapy and engineering principles, to establish tiered training mechanisms and standardised clinical pathways, and to take an active part in formulating ethical guidelines and technology policy, so as to play a leading role in standardising BCI application and in the humanising of its clinical integration.

Keywords: stroke; brain-computer interface; rehabilitation; influencing factors; nursing decision-making; nursing humanism; role expansion; review

1 Brain-computer interface technology and the new situation of stroke rehabilitation nursing

In the context of stroke rehabilitation, the core value of a brain-computer interface lies in its capacity to construct a closed-loop "brain–device–feedback" system in which repeated intention-driven training strengthens or remodels the damaged neural pathways — that is, promotes neuroplasticity, which is the fundamental basis of functional recovery[9]. By mode of signal acquisition, brain-computer interfaces fall into two broad classes, invasive and non-invasive. An invasive brain-computer interface implants electrodes surgically and can acquire high-quality neural signals, with outstanding results in the decoding of fine movement, such as hand function reconstruction after stroke; but its long-term signal degradation, the risk of implant infection and the management of perioperative complications[10] have extended the content of nursing from conventional rehabilitation nursing to advanced neurosurgical practice nursing, and its high cost has given rise to ethical concern about equity of access to health care[11]. A non-invasive brain-computer interface records and decodes brain activity in real time — by electroencephalography, functional near-infrared spectroscopy (fNIRS) and similar means[12] — and shifts the technical burden onto the routines of daily nursing. Non-invasive interfaces such as EEG and fNIRS are extremely sensitive to signal noise and are readily disturbed by electromyographic activity, eye movement and skin impedance, so that "fitting the electrodes correctly" is upgraded from a basic procedure into a critical control point that determines rehabilitation outcome[13-14]. Nursing staff must master electrode impedance testing, including daily calibration of electrode position and checking of contact resistance, together with preventive nursing for the skin pressure injury or allergic reaction that prolonged electrode wear can cause. Refined management of nursing records, such as a log of signal waveform abnormality, becomes an important data source for assessing rehabilitation progress. Emerging minimally

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invasive techniques, endovascular brain-computer interfaces among them, are also under exploration; by minimally invasive means they reconstruct the "thought–movement" pathway, offering a practicable route to functional restoration for patients with severe paralysis in whom conventional rehabilitation has had little effect[15].

Brain-computer interface technology has now been extended to several core scenarios of stroke rehabilitation treatment and nursing, its applications being summarised as motor function reconstruction based on motor imagery, cognitive intervention based on EEG feedback, communication assistance for the aphasia that stroke causes, and neurological function assessment in patients with disorders of consciousness[16-17]. Non-invasive brain-computer interfaces have accumulated a substantial body of clinical evidence in stroke motor rehabilitation and related fields[18-19], whereas invasive interfaces, constrained by technology, ethics and cost, have yet to achieve large-scale clinical rollout in patients with stroke. At the same time different technical routes make different demands on nursing practice: an invasive interface requires nurses to hold advanced surgical nursing skills in perioperative management, monitoring of the implanted device and infection prevention, whereas a non-invasive interface places greater weight on precise placement of electrodes and sensors, maintenance of signal quality, guidance of the patient's motor imagery training and long-term rehabilitation support. Understanding these technical characteristics is the foundation of nursing's effective participation in brain-computer interface treatment for stroke. When nursing staff must identify artefact in event-related desynchronization (ERD) signals, monitor electrode impedance and record abnormal signal waveforms, the content of nursing has already extended from "caring for the body" to "collaborating in decoding the brain".

2 Practice of brain-computer interfaces in stroke rehabilitation treatment and nursing

2.1 Decoding movement intention and remodelling neurological function

Motor dysfunction, and upper limb motor dysfunction in particular, is the field in which brain-computer interfaces have been most widely studied and most extensively evidenced in stroke rehabilitation. Two patterns of application are used. The first is a brain-computer interface system for motor imagery (MI) training, which detects the specific EEG pattern generated when a patient attempts to move the affected limb and gives immediate, intuitive visual or tactile feedback so as to reinforce activation of the motor cortex[18]. Studies show that this pattern can effectively break the vicious circle of dysfunction and lack of training[20]. Several meta-analyses and systematic reviews have confirmed the effectiveness of brain-computer interfaces in the motor rehabilitation of this class of disease[14,21]. The second pattern uses the decoded movement intention to drive a rehabilitation robot, an exoskeleton or a functional electrical stimulation (FES) device directly, providing the affected limb with assisted or passive–active movement and forming a closed "intention–action" loop[22-23].

The effectiveness of either pattern depends heavily on the real-time responsiveness of the patient's central nervous system. In clinical practice, nursing staff are the only professionals able to monitor continuously the fluctuation of the patient's state within the day[24]. Nurses must ensure that the device and the signal are stable, and may use the Visual Analogue Scale for Fatigue (VAS-F)[25], heart rate, skin conductance change and willingness to interact to assess the patient rapidly and to decide independently whether training should proceed at once. During training they provide precise guidance and immediate feedback, and observe the patient's physiological and psychological responses keenly. Structured tools such as the graded exercise prompt card[26] can help nurses to unify their instructions and standardise the procedure, raising the patient's adherence to training and so turning a technical process into a safe, supportive and rewarding rehabilitation experience. This capacity to adjust brain-computer interface training parameters in real time on the basis of nurses' continuous observation extends nursing decision-making from the conventional execution of medical orders to collaborative prescribing, and is an important marker of core rehabilitation nursing competence in the era of brain-computer interfaces.

2.2 Rebuilding the channel of connection and safeguarding the dignity of expression

For patients with disorders of consciousness (DoC) resulting from severe stroke — a minimally conscious state (MCS) or locked-in syndrome (LIS), for example — brain-computer interface technology has become a key route to the recovery of communication[24]. From the conventional EEG speller to the invasive language decoding systems that have broken through in recent years, brain-computer interfaces enable patients to express their needs, take part in decisions and communicate emotionally once more[27]. Invasive microelectrode array technology in particular has made major progress in decoding handwriting intention and in synthesising speech, markedly improving the efficiency of communication. By decoding the neural activity associated with handwriting movements or with articulation, one research team achieved an intention-driven typing speed of up to 90 characters per minute[28]. By decoding the neural signals associated with vocalisation, researchers have even synthesised speech successfully, enabling patients with aphasia to "say" what they wish to say[29-30]. Brain-computer interfaces allow patients to express their needs, take part in decisions and communicate emotionally again[31].

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In this care scenario, whose core is the rebuilding of connection, nursing staff must assess the cognitive and emotional load that the device imposes on the patient, and provide continuing, individualised technical guidance and psychological support so as to help patient and family adapt to and make good use of this new means of communication. This process is closely consistent with the "timing model", which emphasises dynamic matching to the patient's care needs at each stage[32]. Nurses must identify keenly the psychological change and the need for support that the patient experiences while adapting to brain-computer interface communication, build a bridge of understanding between patient, family and technology, and offer continued psychological support and patient explanation; and they must translate the signals the device outputs into a genuine understanding of the patient's state and an individualised care plan, so supporting the patient in recovering completeness and connection at the psychological and social level.

2.3 Assessing consciousness and intervening in the cognitive process

Post-stroke cognitive impairment (PSCI) has a high incidence and seriously affects rehabilitation prognosis and quality of life[33]. The application of brain-computer interfaces in this field is at an active stage of exploration and shows a distinctive potential. In assessment, a brain-computer interface provides an objective tool for identifying residual cognitive capacity in patients with disorders of consciousness: by detecting brain activity while the patient performs a specified mental task, it helps to identify a latent minimal consciousness state, which is of considerable importance for clinical judgement and nursing decisions[34]. In treatment, by designing specific cognitive tasks, brain-computer interface technology can objectively and quantitatively monitor the patient's brain load and neural efficiency while performing a cognitive task such as an attention or working memory task[35]. This means that a brain-computer interface can be used not only for motor imagery but also for feedback in "cognitive imagery" or in attention training[16]. Nurses or therapists can use the real-time neurofeedback the interface provides to adjust the difficulty of the cognitive training task and so achieve individualised, adaptive training. Intensive cognitive intervention led by nursing staff can effectively improve cognitive function, activities of daily living and neurological deficit in patients with PSCI[36]. Furthermore, research on the application of the patient navigation model in stroke rehabilitation[37] shows that when nursing staff act as navigators they can effectively integrate multidisciplinary resources and improve patients' adherence to treatment and continuity of rehabilitation. This extends nurses' assessment capacity from observing the surface of behaviour to taking part in interpreting signs of neural activity, and the combination of their observation with brain-computer interface data can inform prognosis and the difficult ethical decisions about whether treatment should be maintained or withdrawn. Brain-computer interface technology is thus drawing nursing into the more advanced processes of neurological function assessment and clinical ethical decision-making[33-34], promoting a deeper integration of the nursing discipline with neuroscience and ethics, and enabling nursing to play a more active part in neurological assessment and in complex clinical decisions.

3 Factors influencing the application of brain-computer interfaces in stroke rehabilitation

3.1 Technical factors

Technical factors are the double-edged sword that both drives and constrains the application of brain-computer interfaces in the treatment of neurological disease. Between 2023 and 2025, brain-computer interface technology made marked breakthroughs in the treatment of specific neurological diseases. Thought-to-text conversion at a speed approaching natural conversation, for instance, offers patients with DoC a revolutionary means of communication treatment[28]; and AI models have greatly improved the efficiency of neural signal decoding and the accuracy with which patients with stroke drive external devices through motor imagery for functional rehabilitation[4]. The clinical application of these advanced technologies is, however, severely constrained by engineering bottlenecks[38]: the long-term signal degradation of the implanted electrodes used to treat motor dysfunction obliges the system to recalibrate frequently[39], and the equipment is complex to operate and unfriendly to the user. Technical instability and complexity of operation add directly to the burden of nursing work — troubleshooting equipment failure, frequent recalibration, retraining of the patient — and make greater demands on the professionalism of nursing staff.

3.2 Nursing staff factors

As brain-computer interfaces come into use as a new therapeutic tool in stroke treatment and rehabilitation, the nursing role is being forced to evolve from that of conventional carer towards that of technology integrator, data interpreter and multidisciplinary coordinator[40]. During treatment, nursing staff must help to manage the implanted device, observe the patient's neurological response and prevent complications. This role change, however, lacks institutional support and systematic training, and China has yet to develop a mature specialised nursing model for brain-computer interfaces. Nursing staff generally face a difficulty of insufficient knowledge and skill, and their central coordinating part in the

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multidisciplinary team is not fully recognised[2]. This shortfall in competence, together with the lag in role definition, makes it hard for nurses to deal effectively with the complex problems of human–machine interaction that brain-computer interfaces bring; it affects the quality of nursing and may also become a hidden brake on the uptake of the technology.

3.3 Patient factors

The disease characteristics and highly individualised neuropathophysiological patterns of patients require that a brain-computer interface programme be highly customised[38,41]. This makes greater demands on nursing assessment: nurses need keen powers of observation in order to identify each patient's distinctive pattern of neural response, threshold of psychological motivation and best mode of interactive learning, and so provide genuinely individualised support for treatment. The patient's psychological state — motivation, attention and emotion — directly and significantly affects the performance of the brain-computer interface system, while negative emotion such as frustration during use seriously weakens long-term adherence[42]. Patients hold very high expectations that a brain-computer interface will restore their independence and their social capacity[39], but the instability of the technology, a poor user experience and the absence of long-term support systems[43] readily lead to those expectations being disappointed and to a fall in adherence. Patient-centred individualised psychological support and realistic expectation management are therefore the key to improving nursing effectiveness.

3.4 Organisational and environmental factors

At the macro level, the national strategy explicitly incorporates the functional rehabilitation of post-stroke hemiplegia, aphasia and similar conditions into the priority applications of brain-computer interface technology. At the level of implementation within health-care institutions, the mandatory technical certification standards and the detailed conditions of medical insurance access for brain-computer interface rehabilitation remain incomplete; the high cost of purchasing and maintaining equipment constitutes the principal economic barrier[44]; the pace at which local reimbursement policy is implemented, and the sustainability of payment, remain to be seen; and conventional departmental boundaries hinder the effective collaboration of the multidisciplinary team that brain-computer interface rehabilitation requires[45]. The system of social support, and in particular the capacity and the burden of family carers[45-46], also bears profoundly on whether a patient can continue brain-computer interface rehabilitation treatment at home, and so determines the long-term maintenance of the treatment effect.

3.5 Ethical and legal factors

Because it intervenes directly in the brain, brain-computer interface technology also touches a number of ethically sensitive areas in the treatment and rehabilitation of patients with stroke. There is an urgent need for "neural privacy", and for protection of the neural data generated during stroke rehabilitation training that goes far beyond that given to conventional medical data[47-48]. The intervention of the technology in the mind may blur the boundary between human and machine; in patients with stroke who have cognitive impairment or emotional fluctuation in particular, autonomy and agency in rehabilitation may be affected, and a misjudgement or failure of the device raises the difficulty of attributing responsibility[49]. To meet these challenges, constructing an emerging legal and ethical framework centred on "neurorights", and deepening a dynamic and comprehensive process of informed consent, have become the fundamental precondition for ensuring that the technology develops in a human-centred and beneficial direction.

4 Nursing challenges in the clinical application of brain-computer interfaces, and countermeasures

4.1 Closing the knowledge and skill gap and building an interdisciplinary training system

Nursing staff at present have both a general blind spot in their knowledge of brain-computer interface technology and a shortfall in skills, which directly affects the safety and effectiveness of clinical use[11,50]. An interdisciplinary nursing education system for brain-computer interfaces should accordingly be built systematically, incorporating modules on neuroscience, engineering principles and ethics into nursing curricula, and a specialist certification mechanism covering simulation training and supervised clinical practice should be established. Nursing education should in future work more closely with engineering, neuroscience and other fields to develop joint training programmes and continuing education platforms, and so cultivate interdisciplinary nursing talent that both understands the technology and is skilled in care.

4.2 Filling the gap in standard procedure and establishing whole-cycle operating standards

The field of brain-computer interface nursing at present lacks a unified, evidence-based standard operating procedure and quality evaluation system; practice depends on individual experience, the quality of nursing varies, and the professional

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development of the field is held back[50]. The countermeasure is for the nursing profession to take a leading part, working with other disciplines to draw up a clinical pathway and operating standards covering the whole brain-computer interface cycle, and to establish in support the process and outcome indicators of nursing quality so as to achieve standardised management. Further pilot research on brain-computer interface nursing clinical pathways is needed, so that a standardised nursing package and assessment tools reproducible in different institutions can be developed and brain-computer interface nursing practice moved towards regularisation and standardisation.

4.3 Meeting the challenge of role expansion and designing a model of human–machine collaborative nursing

The clinical application of brain-computer interfaces adds wholly new tasks — device maintenance, supervision of training, data recording — which may increase the workload of nursing staff and even induce burnout[50]. At the same time the technology diversifies the nursing role: nurses must simultaneously act as technical collaborator[11], promoter of rehabilitation, assessor of body and mind[29], patient educator and interdisciplinary communication hub[21,50], which brings the practical challenge of role overload. Nursing managers should define the division of the new nursing roles in the brain-computer interface setting, carry out a systematic redesign of nursing workflow, and construct a model of human–machine collaborative nursing — "assess, interact, adjust" — centred on the professional judgement of the nurse. The model is intended to delineate the functional boundary between nurse and brain-computer interface system and to achieve complementary strengths and aligned objectives: the brain-computer interface system is responsible chiefly for the objective acquisition of signals, the precise decoding of intention and the generation of standardised feedback, while the nurse, drawing on clinical wisdom and humanistic care, leads the individualised management and dynamic adjustment of the whole rehabilitation process. Nursing should in future take the lead in developing the "human–machine collaboration" model of care, and lead the design of systematic workflow, structured recording tools and mechanisms of remote collaboration, so that nursing staff play the leading and coordinating part in the application of the technology.

4.4 Anticipating ethical risk and drawing up evidence-based guidelines and a review framework

The application of brain-computer interfaces is accompanied by many ethical problems, which form an indispensable part of its development. Chief among them are how to obtain effective informed consent from patients with communication or cognitive impairment, and how to ensure the privacy and security of neural data in the routines of nursing[51]. The nursing field at present lacks specific, practicable ethical practice guidelines. Clinical practice guidelines should be drawn up addressing the core ethical issues of informed consent, privacy protection and data sovereignty; a multidisciplinary ethics review committee should be established; and neuroethics should be applied within the training and education of nursing talent, so as to improve ethical decision-making capacity.

5 The evolution of stroke rehabilitation nursing under the drive of brain-computer interfaces, and the contribution of the discipline

Viewed from the standpoint of the nursing discipline, the clinical integration of brain-computer interfaces in stroke is not a simple addition of technology but is driving a profound evolution of nursing practice at three levels. These developments are both nursing's adaptive response to technological change and a marker of the systematic expansion of the discipline's content.

5.1 The shift of level in nursing assessment

Conventional rehabilitation nursing assessment relies mainly on behavioural scales and clinical observation. The entry of brain-computer interface technology is moving nursing assessment from the level of behavioural observation down to the level of neural signal: when nurses must monitor electrode impedance, identify ERD signal artefact and record abnormal signal waveforms, the content of nursing has already extended from "caring for the body" to "collaborating in decoding the brain"[52]. Nursing staff are beginning to acquire the capacity to recognise signs of recovery at the level of the neural signal, which offers a new observation window for early intervention and precision rehabilitation.

5.2 The substantive realisation of nursing decision-making authority

The effectiveness of brain-computer interface rehabilitation depends heavily on the choice of training timing and on the dynamic adjustment of parameters. Nursing staff are the only professionals able to monitor continuously the fluctuation of the patient's state within the day, and in motor rehabilitation they have begun to take independent clinical decisions: they judge whether the patient may train today on the basis of fatigue scales, heart rate and skin conductance change, and adjust dosage dynamically minute by minute during training[18,24]; in the assessment of consciousness, they capture through continuous observation the signs of consciousness that a single assessment misses, and on that basis initiate

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multidisciplinary reassessment[33-34]. These specific and exclusive decision rights mark the point at which the expansion of the nursing role has moved from conceptual advocacy to a substantive extension of professional responsibility. Nursing is no longer the passive executor of medical orders but a co-author of the rehabilitation plan.

5.3 The elevation of the humanistic function of nursing

In brain-computer interface communication scenarios the core value of nursing staff lies not in operating the device but in translating the discrete neural signals the interface produces into an understanding of the patient's state and a care plan with warmth. The nurse becomes the one professional role able to understand both the brain-computer interface system and the patient, building a bridge of understanding between technology and person; this is the new form of nursing humanism in the era of brain-computer interfaces, and the core of nursing that technology can never replace.

5.4 The significance for reconstructing the nursing knowledge system

These developments pose a systematic challenge to the nursing discipline. In the structure of knowledge, nursing must incorporate the fundamentals of neural signals, the principles of devices and human–machine interaction, and other content from engineering and neuroscience; in the framework of competence, it must build composite abilities covering signal quality monitoring, neurofeedback guidance and support for ethical decisions; and at the professional boundary, nursing is moving from an "auxiliary link" in rehabilitation towards a "core collaborative link". This requires nursing education, clinical practice and discipline building to respond systematically.

6 Conclusion

Brain-computer interface technology is developing rapidly and has already shown considerable clinical potential in restoring function in patients with severe motor, cognitive and communication impairment after stroke; its range of application is widening from upper limb motor rehabilitation to lower limb functional training, cognitive intervention, communication assistance and other diverse scenarios. At the same time the clinical translation of brain-computer interfaces still faces multiple constraints: technical stability, the gap in nursing knowledge and skill, the absence of standardised procedure and lagging ethical regulation. Viewed from the standpoint of the nursing discipline, three levels of evolution in nursing practice may be summarised — a shift of level in assessment, the substantive realisation of decision-making authority, and the elevation of the humanistic function. To meet these changes the nursing profession must act on the following fronts. At the level of the knowledge system, it should build an interdisciplinary education system and strengthen ethical guidance and empirical research. At the level of institutional safeguard, it should write nursing decision rights such as admission to training and dosage adjustment into job descriptions, and define in the multidisciplinary team the route by which nurses take part in neuroethical decisions. At the level of practice model, it should advance the construction of standardised clinical pathways and explore a nurse-led model of "human–machine collaboration" care.

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