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A Survey on the Use of Haptic Feedback for Brain-Computer Interfaces and Neurofeedback

Mathis Fleury, Giulia Lioi, Christian Barillot, Anatole Lécuyer.

Abstract—Neurofeedback (NF) and Brain Computer Interface (BCI) rely on the registration and real-time feedback of an individual brain activity with the aim of achieving self-regulation of specific neural substrate or controlling external devices. These approaches have historically employed visual stimuli. However, in some cases vision is not suitable or inadequately engaging. Other sensing modalities like auditory or haptic feedback have already been explored and multisensory stimulation is expected to improve the quality of the interaction loop. Moreover, in the case of motor imagery task, closing the sensory-motor loop thanks to haptic feedback may be relevant for motor rehabilitation application, as it can promote plasticity mechanisms. This survey presents the various haptic technologies and then describes their application to BCI and NF. We identify major trends in the use of haptic interfaces for BCI and NF and discuss crucial aspects to inspire further studies.

Index Terms—Neurofeedback, BCI, Haptic Feedback, EEG, fMRI, Multisensory, BMI, touch.

I. INTRODUCTION

Since the past decade, advances in brain science and computer technology have led to a growth in the development in Neurofeedback (NF) and Brain Computer Interface (BCI) applications. Some recent technological advances such as machine learning analyses, wireless and real-time recordings have increased interest in NF and BCI approaches, especially EEG-based BCI/NF. One of the cornerstones of NF and BCI is the feedback given to the subject. The subject relies on the feedback to learn and improve his mental strategy. Traditionally, visual feedback has been mostly employed in BCI/NF applications, but its use may seem questionable in some cases. For example, a visual feedback is not always suitable for individuals with an impaired visual system or during a mental motor imagery task, which requires a great abstraction from the subject. In this case, a tactile feedback could seem more appropriate and more natural than visual feedback [1].

Visual feedback has been shown to be the sensory input that produces the best learning processes [2]. However, other feedback modalities have been less explored and there are many situations other types of feedback are required, due to the pathology itself or requirements of the rehabilitation process, e.g. for locked-in patients [3]. Besides, it has been suggested that providing haptic feedback could improve the sense of agency, a technology acceptance-related factor, in motor imagery (MI) BCI's [4].

Applications related to haptic-based BCI are multiple: such as rehabilitation and entertainment. The majority of the clinical papers included in this survey focuses on stroke patients, because haptic-based BCI/NF seems to be a promising way for rehabilitation, as this non-invasive technique may contribute to close the loop between brain and effect [5]. Preliminary studies report that BCI performance is not affected by the specific type of feedback [6], i.e. whether visual, auditory or haptic. Nevertheless, the combination of multiple feedback, which can be called multisensory feedback is expected to provide enriched information [7]. However, an efficient feedback should be not too complex, and should be provided in manageable pieces [8].

Haptic technology has evolved since the past decades and haptic displays are becoming more and more sophisticated, less intrusive and thus more effective and more acceptable by the user. In this paper, the term "haptic feedback" is used to categorise two different types of feedback: tactile and kinaesthetic feedback.

Historically, NF has been used to develop internal control while BCI is primarily intended to train control over external objects (orthosis, computer, etc.). By definition the NF is a biofeedback from brain areas [9], with the purpose of self-modulation of brain activity, i.e. a personal control and not a redirection on an object. Following the definitions given to NF and BCI, this survey will distinguish the concepts of NF or BCI on the basis of the rationale of their implementation. For example, when a patient with a stroke uses an exoskeleton as a feedback, the goal is not to control that skeleton for controlling it but to work the perilesional areas in order to activate the plasticity systems. In this case, as the purpose is to enhance neuronal activity, the term NF is appropriate. However, if the paradigm is to control the orthosis, then we will speak of BCI.

In their recent paper, Van Erp and Brouwer [10] provide an extensive state-of-the-art of touch-based BCI. Our survey aims to complement this review with an extension to all haptic modalities/cues and both BCI/NF applications. Our objective is to better understand the current possibilities of haptic feedback and further improve the design of future studies.

This remained of this paper is organised as follows. First, we provide an overview of existing haptic technology II. Secondly, we surveyed recent studies exploiting haptic feedback in BCI/NF III, showing the experimental and technical challenges. These articles are then discussed IV where we also propose guidelines on the use of haptic, and identify some remaining challenges. Finally, a conclusion is given V.

II. AN INTRODUCTION TO HAPTIC INTERFACES

The study of haptic interfaces is an expanding research area focusing on human touch and interaction with the environment through touch. Its integration within BCI experiments is rather recent (2007) and was pioneered by Cincotti et al. [1] and Chatterjee et al. [11]. The term haptic can be defined as 'sensory and/or motor activity of the skin, muscles, joints and tendons' (ISO, 2011 244 :1). An information delivered through a haptic device is resolutely different from a visual display. The design of a haptic feedback depends on an in-depth knowledge of the human haptic sense, either of the tactile sense or the kinesthetic sense.

A. Haptic Perception

The purpose of a feedback in a standard BCI/NF protocol is to give a cue of a specific brain activity in order to have a beneficial impact on the learning of a task of BCI/NF [12]. Thus, the impact of a feedback is not only dependent on its content but on the way it is presented to the subject [?]. In this sense, the knowledge of the human haptic sense is a fundamental step in the elaboration of a haptic interface for BCI/NF. Haptic interfaces have possible interactions with many parts of the body which implies that our sense of touch has the potential to become a very useful tool for digital interaction. The human skin is capable of detecting mechanical stimulation, heat and pain [13]. When a haptic event arises, an emission of a sequence of voltage pulses is generated and transmitted through the nerves directly to the brain the information is processed. For example, picking up an object and feeling its properties (shape, texture, weight, etc.) requires integrating information from tactile and kinaesthetic senses. The primary motor cortex is the physiological location where haptic information is processed. A visualisation of a schematic coronal cut of the distribution of the parts of the body in the primary motor cortex shows an important proportion being used by the hands and the fingers (Figure 1).

The tactile sense is associated with receptors distributed under the surface of the skin. This sense is commonly called "sense of touch", since tactile receptors (high frequency sensors) discriminate very fine surface properties such as small shapes and fine textures and with a particularly high density under the palm and the fingers [14]. In the case of the hands, four types of physiological receptors can be found, as described in [15]: "our fingertips can sense a wide range of tactile stimuli, such as temperature, pressure, pain, or vibration".

The kinaesthetic sense or proprioception or force is associated with receptors in muscles, tendons and joints and provide information about movement, position and torque of limbs [16]. The term "proprioception" is also used for properties regarding the whole body whereas kinaesthetic refers to the perception of properties of limbs, however, this differentiation will be neglected in this survey.

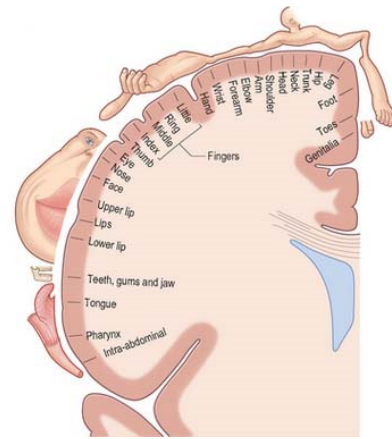


Fig. 1: Functional brain areas in the motor cortex [17]

B. Haptic interfaces and actuators technologies

This section presents the wide spectrum of existing haptic technologies. Haptic feedback can take different shapes, but two main categories can be distinguished: tactile-feedback or force-feedback. Before describing them in more details, several important properties of haptic interfaces will be provided.

1) General properties of haptic interfaces:

a) *Grounded vs. Wearable Interfaces*: This categorisation is based on whether the haptic interfaces are mobile or are anchored to the environment. The design of haptic interfaces recently started to take into account portability as a crucial parameter [18]. Furthermore, wearable devices should not limit the user's motion and enable to stimulate grasping-related sensations whereas grounded devices restrain the user's motion but enable to stop and block him. *Ground-based interfaces* are haptic interfaces anchored in the environment. Ground-based haptic interfaces can generally be classified as link-type, magnetic-levitation-type, and tension-based-type [19]. The PHANTOM, a 6 degree-of-freedom (DOF) force-feedback pen that provides a force-reflecting interface between a human user and a computer is an example of a performing link-type haptic interface [20]. *Wearable haptic interfaces* are grounded on the body of the user. Wearable devices are not limited to a constrained workspace, therefore they allow users to move freely and perceive haptic feedback in a much larger range. On the other hand, wearability introduces power limitations. Devices must be built with miniature technology and actuation is limited due to weight and power consumption. Pacchierotti and colleagues [21] provide a list of guidelines for the design of wearable tactile devices that includes multiple factors such as the form factor, the weight, the impairment, and the comfort (Figure 2).

b) *Active vs Passive Touch*: Haptic feedback can be divided in two categories: active and passive. Usually active touch refers to the act of touching, while passive touch refers to being touched [24]. In the first case, the sensation is brought by the perceiver and in the other case by an external device. Hence, passive haptics refer to the haptic properties of physical objects, such as a keyboard or a cup of coffee, and active haptics refer to the haptic that are actively generated by the device, based on haptic actuators and software. In the haptic field most interfaces are active, which is not the case for

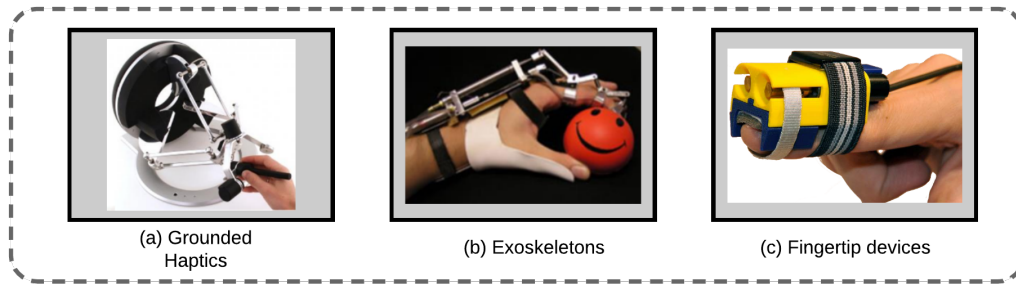


Fig. 2: From grounded haptic interfaces to more wearable and portable designs. (a) Omega.6 with a stylus interface (*Force Dimension*, Nyon, Switzerland); (b) Hand exoskeleton for natural pitching [22]; (c) Cutaneous display [23]

haptic-based BCI/NF. Indeed, haptic-based BCI/NF interfaces use calculated feedback from the brain activity and not from the sense of touch. *Passive touch* refers to the fact that the haptic feedback is not calculated according to the user. For example, a standard vibrotactile alert from a mobile phone can be considered as a passive feedback.

c) Direct contact, intermittent contact and indirect contact interfaces: In the design of a haptic interface, the nature of contact between the user and the interface can be of three types. *Direct contact interfaces* correspond to an attached haptic interface the user is always in contact with the device. *Intermittent contact interfaces* where the contact is limited with the device and only provided when required. For example, Frisoli and colleagues developed a grounded fingertip haptic interface a plate enters in contact with the user whenever the finger touches a virtual surface [25]. *Indirect/Mid-air interfaces* produce haptic feedback to the user without any contact with him and therefore does not constrained the wearing of gloves or the holding of a device [26]. UltraHaptics [27], a grounded ultrasonic device is an example of a mid-air device that provides multi-point haptic feedback on the user's skin. A state-of-the-art on mid-air devices can be found in [26].

2) Tactile interfaces: Tactile feedback stimulates the skin surface through a direct contact. Tactile interfaces can be separated depending on the sensations they provide: vibration, contact, pressure, temperature, curvature, texture, softness / hardness, friction [28]. Generally, tactile devices must be light weight and small, and if the tactile display is to be worn by mobile users, it must minimise power consumption [29]. This review will focus on vibration, contact, pressure interfaces as these are the most common tactile interfaces in the BCI/NF community. Only feedback related to vibration, contact, pressure, temperature and electrotactile will be described in this section. These are the most commonly used feedbacks in the BCI/NF community today.

a) Vibratory feedback: Vibrotactile feedback is generated by mechanical vibration normal or transverse to the surface skin area. Mechanical vibration conveys tactile information modulating vibration frequency, amplitude, duration, timbre or spatial location. Vibrotactile feedback uses the same principle as audio headphones, i.e converting electrical signals to sound waves. The quality of vibrotactile stimulus perception is influenced by the frequency of the vibration ((50-300)Hz

which corresponds to the bandwidth of the human tactile sense), by the body position and underlying tissues. The use of oscillating pressure (sinusoidal or square and amplitude modulations) also adds new DOF to the design of vibrotactile stimuli, such as waveform shape and amplitude modulations at different modulation frequencies of the carrier frequency [28]. Vibrotactile devices delivering variable pressure on the skin have been employed for instance as an alternative sensitive channel for blind or deaf individuals [30]. The sensitivity of vibrotactile stimulation depends on body position and age of the subjects [31].

b) Contact and pressure feedback: To stimulate contact by pressure, large scale devices are generally used that contrast with the small part of the skin on which they act, such as fingertips (Figure 3.b). The active stimulation principle technology is materialised in large dimensions, due to the quantity of active elements that high power consumption causes and sometimes makes portability difficult. An example of this appreciation can be highlighted in interfaces for a finger that generate a Braille stimulus, that use power units to drive needles or pins [32] and others that use a tactile matrix, driven in an initial development by a fixed ball that is transmitted in two dimensions and, in a second development, by pneumatic effect with three resolution bits [33].

c) Thermal feedback: Thermal interfaces provide thermal cues to the user that are usually experienced during interactions with objects. Following this principle, Guatni and colleagues [34] created a haptic interface that provides thermal and force feedback for surgical operation (Figure 3.c). The thermal feedback was coordinated to the thermophysical properties and temperatures of living organs in order to help the surgeon's perception. Thermal feedback was also proposed to add thermal sensing system for prostheses [35]. For the prosthesis users, thermal stimulation improves the interaction with the surrounding environment and provides them with useful information for daily activities such as material discrimination, pain avoidance, and psychological comfort. A state-of-the-art on thermal displays can be found in [36].

d) Electrical feedback: A light electrical stimulation, also known as electrotactile stimulation, can raise the user's awareness and can be used for tactile feedback. Several electrotactile displays have been developed as sensory aids for hearing [37] and visual disabilities [38]. Variations in intensity and

temporal parameters of stimulation and in the spatial sequence of electrodes activated can be used to convey information. However, both the absolute threshold and subjective magnitude of electrotactile stimulation increase rapidly with changes in current amplitude [39]. Stimulation current must be controlled carefully to avoid painful sensations. The level of intensity is usually established during a practice session before the recordings. The electrotactile stimulation can also be used as a tongue display unit (Figure 3.d), consisting of a signal generator that controls the voltage output, a flexible connector cable and the electrode array. A survey on electrical feedback can be found in [21].

3) *Kinaesthetic Interfaces*: Contrary to tactile feedback, force-feedback addresses the kinaesthetic sense, involving positions, velocities, forces and constraints sensed through muscles and tendons. A kinaesthetic feedback can provide information about the limb position or strength applied. These devices are usually grounded since the display of the force or motion is delivered through a tool (i.e. PHANToM [20] or Omega). However, grasping haptic devices and exoskeletons include wearable devices (i.e. haptic gloves). Haptic clinical devices such as orthoses or robotic systems have notably been used to guide the movements of paralysed limbs of the patients [45].

a) *Grounded force feedback*: Force-feedback devices serve usually two main purposes: to measure the positions and contact forces to the user's hand (and/or other body parts), and also to display contact forces and positions to the user. These haptic interfaces are usually composed of rotating joints that connect rigid links [20]. Force-feedback devices can be categorised according to the DOF provided by each device, from a simple 1 DOF device to a complex 7 DOF device. Other designs such as cable systems or stringed haptic interfaces also meet this definition, as tension-based systems (Figure 3.a). Cables are fixed around the corners of a structure, such as a cube. Each cable includes a torque motor, cable, tensioning mechanism, plus cable length and force sensor. Tension-based haptic interfaces [46], have the advantages of fast reaction speed, simple structure, smooth manipulation, and scalable workspace [47].

b) *Exoskeletons devices*: Exoskeletons are more or less anthropomorphic, in order to provide forces on natural degrees of freedom on the body (Figure 3.b), they have to fit naturally the hand without impairing it or interfering with its actions. Exoskeletons can be heavier [48] and decrease the comfort of the user. The terms orthosis or exoskeleton are in general used to indicate the system effectors, often in an ambivalent way. This review will use the definition from Herr [49] stipulating that "generally exoskeleton augments the performance of an able-bodied wearer, whereas orthosis are used to assist a person with a limb pathology and help correct, rehabilitate or support parts of the body". A state-of-art on wearable kinaesthetic interfaces can be found in [21].

c) *Functional electrical stimulation*: (FES) is a more intensive stimulation (up to 150V [50]) than electrotactile stimulation [51]. This electrical stimulation actuates muscle contraction and thus provides a kinaesthetic sensation. FES has been efficiently used for motor rehabilitation after stroke

in [44] [52] [53]. [54] (Figure 3.c), showing promising results for motor recovery.

III. HAPTIC FEEDBACK IN BCI/NF

The following section describes the state-of-the art haptic applications to different BCI and NF paradigms. To date, the MI paradigm is the most used paradigm for haptic feedback, its interest being in the possibility to close the sensory-motor loop: the user imagines a movement and the modulated signal can be employed to control haptic interfaces that in turn give the subject a sensory-motor stimulus. Other paradigms requiring less training, such as P300 and SSSEP, have also been used in association with haptic interfaces. These haptic sensors are used to stimulate parts of the body (different frequencies) and the elicited EEG signals are processed to generate control commands. Haptic displays have therefore different purposes in these two kind of BCI: in sensory motor paradigms is to give a haptic feedback from the brain activity of the subject whereas for P300 and SSSEP haptic interfaces are used as stimulation and the evoked brain activity is further decoded for a command (Figure 4).

BCI can be divided into three classes: active, reactive, and passive [10]. Only BCI applications that are based on brain pattern and are actively or reactively generated by the user will be considered in this review: the active BCIs (aBCI) and reactive BCIs (rBCI). aBCI provide a non-muscular communication between the brain and the external environment without external stimuli, for instance in Sensory-Motor Rhythm (SMR) paradigms [55] [56] [57] [58]. A rBCI use external stimuli to provide informations to the subject, for example, in SSEP or P300 paradigms. Passive BCIs (pBCI), which measure the cognitive or emotional state of the subject from brain patterns without any need for specific user activity [59], will be disregarded, as it is out of the scope of the present work.

For an interactive system, our sense of touch is ideal because of its nature. For example, our haptic sense is bidirectional because human can perceive and actuate via touch [60]. In terms of interface design, this means that touch can be used as an input and output tool.

A. Motor Imagery Paradigms

Sensorimotor rhythms (SMR) remains the most popular motor imagery paradigm in haptic-based BCI/NF. SMR refers to localised brain rhythms desynchronization in the upper alpha band (10–12 Hz) usually accompanied by changes in synchronisation in the beta band (13–25 Hz) [55] occurring when performing a real or imagined motor task. This paradigm seems well adapted to haptic based-BCI where tactile and kinaesthetic feedback can potentially mimic the natural representation of limb state variables [73]. Most of the SMR-based haptic system use kinaesthetic sensation as feedback from MI performance. The first SMR-based orthosis (hand orthosis, 1 finger) was designed by Pfurtscheller and colleagues [68] for a tetraplegic patient: it was shown that after a period of training (5 months) the patient was able to efficiently control the orthosis with foot or hand MI. Kinaesthetic systems differ

TABLE 1: SMR based haptic *Note.* K: Kinaesthetic, H: Hand, F: Finger(s) P: Portable, G: Grounded, D: Discrete, C: Continuous, PP: Physical practice, *: MEG., T-Vib: Tactile vibrotactile, V: Visual, T: Thumbs, I: Index, M: Middle finger, NP: Number of Patient, NS: Number of Subjects, SP: Stroke patients, FC: Feedback Comparison, HI: Haptic Influence, HD: haptic design, DOF: Degree Of Freedom

Haptic sensation	Actuator technology	Portability	MI Task	Multimodality	Haptic Gain	C/D	Paper purpose	NP/NS	Reference
K	H orthosis (3 F)	G	Grasp H	V (grasping H), PP	N/A	C	Rehabilitation	4/- SP	[61]
K	H orthosis (H flexion)	G	Open H	V (bar)	Sup	D	Research HI	-/10	[62]
K	H orthosis (all F)	G	Open/close H	none	N/A	C	Research HD	-/23	[43]
K	H orthosis (all F)	G	Reach/grasp/bring H	none	N/A	C	Rehabilitation/Clinical	16/16 SP	[63]
K*	H orthosis (4 F)	G	Open/grasp H	V (bar)	N/A	D	Rehabilitation/Research SP/HD	8/- SP	[64]
K	H orthosis (H flexion)	G	Open F	V (grasp H)	=	D	Rehabilitation/Research FC	12/- SP	[65]
K	H orthosis (all F)	P	Open H	V (clue/color change)	N/A	C	Rehabilitation/Clinical	55/19 SP	[53]
K	H orthosis (2 F)	P	Open H	V (clue)	N/A	C	Rehabilitation/Research brain location	10/- SP	[66]
K	H orthosis (2 F)	P	Open/grasp H	V (bar)	N/A	D	Research HD	-/11	[67]
K	H orthosis (1 F)	P	not specific	V (bar)	N/A	D	Rehabilitation	1/- tetraplegic patient	[68]
K	Arm orthosis	G	Flexion/extension forearm	V (arrow)	N/A	D	Rehabilitation/Research HI	2/6 SP	[5]
K	Arm orthosis (2 DOF)	G	Arm direction	V (target)	N/A	D	Rehabilitation	54/- SP	[69]
K	H knob	G	Grasp H	V (cue)	N/A	D	Rehabilitation	21/- SP	[70]
T-Vib	Mechanical vibrators (on the biceps)	P	H R/L	V (bar)	N/A	C	Research HD	-/6	[11]
T-Vib	Mechanical vibrators (upper part of the trunk)	P	H R/L	V (bar)	=	D	Research/Rehabilitation FC	30/3 spinal cord injuries patients	[1]
T-Vib	Mechanical vibrators (neck)	P	H or foot	V (bar)	=	C	Research FC, HI	-/6	[71]
T-Vib	Eccentric rotating mass (neck)	P	Tapping with F	none	N/A	D	Research	-/11	[72]
T-Vib	Gloves with 5 eccentric rotating mass vibrator per H	P	H R/L	V	N/A	C	Research/Entertainment FC	-/18	[12]
E-T	Tongue display unit array	P	H and foot	V (bar)	=	C	Rehabilitation/Research HD & FC	1/10 Blindness patient	[42]
FES	ES of the forearm	P	open H	none	N/A	D	Rehabilitation	16/- SP	[44]
FES	ES of the forearm	P	H and foot	none	N/A	D	Rehabilitation	1/- tetraplegic patient	[50]

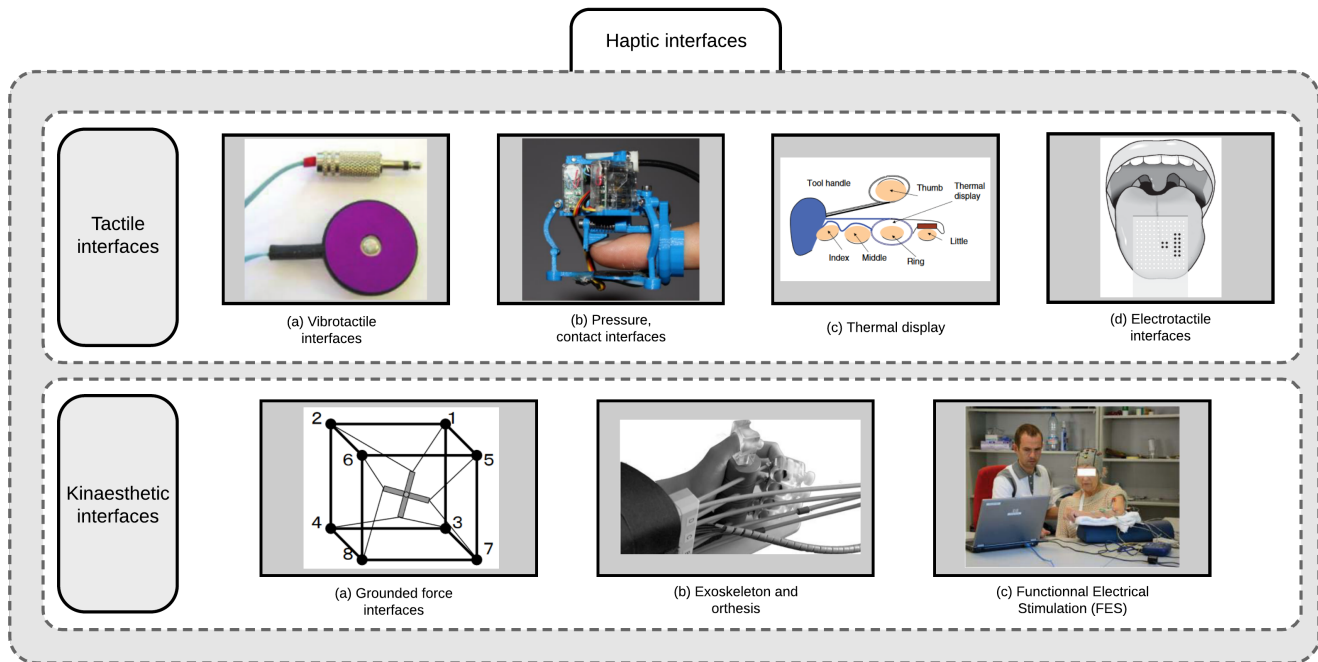


Fig. 3: Four representative tactile stimulation interfaces (a) Vibrotactile Actuators (C2-tactors [40]); (b) Pressure and contact interfaces [41]; (c) Thermal display integration in a medical precision tool for invasive procedures simulation [34]; (d) Tongue stimulated with an array of electrodes [42]. Three representative kinaesthetic stimulation interfaces. (a) Cable system, basic Structure of SPIDAR-G [19]; (b) Orthosis developed by Ramos et al. [43]; (c) FES in a post-stroke rehabilitation application [44]

in their design that can for instance involve the whole hand or just a few fingers. In most of the studies examined, since the input signal was uni-dimensional, these systems used only one DOF, even if the system could deliver more (i.e. 7 DOF arm orthosis from [5]). Different types of movements can be then transmitted, such as grasping or opening the hand. Grounded systems are usually used for kinaesthetic feedback since orthosis are heavy [61] [62] [43] [64] [65] [70] [69]. However, the portability is an important factor for haptic interfaces, that should not limit the motion of the owner. Based on this, some studies investigated portable kinaesthetic feedback [66] [53] [67].

Haptic feedback can be delivered both continuously (where the feedback is given during the execution of the mental task and directly reports the neural activity) and discretely (where the feedback is given after a threshold). For example, [74] proposed a system composed of a mechanical hand orthosis attached to the upper limb to extend and close all fingers in order to investigate the effect of proprioception on BCI control. They showed that in healthy subjects SMR based BCI/NF training with contingent haptic feedback improves BCI performance and motor learning, enhancing SMR desynchronisation during MI.

The use of tactile feedback for SMR based BCI/NF has also been developed in the past years, because of its higher portability, comfortably and affordability with respect to kinaesthetic interfaces. Tactile interfaces have been firstly used to unload the visual channel [71] [72] [1], for individuals with impaired vision [42] or patients with spinal cord injury [1]. Chatterjee

and colleagues [11] demonstrated that users can control a BCI system using only tactile feedback with vibrotactile stimulators placed on the right or left upper arm. They found out that vibrotactile feedback helped the subject to regulate contralateral imaginary tasks. In a lingual electrotactile study, Wilson et al. and colleagues [42] demonstrated that task performance with tactile feedback was comparable to visual feedback. In an extended experiment with 30 healthy and three spinal cord injured participants, Cincotti and colleagues [1] showed that the vibrotactile channel can function as a valuable feedback modality, especially when the visual channel is loaded by a secondary task.

Even if the first study implying haptic feedback for clinical applications was a case report with a tetraplegic patient [68], a large part of these studies focus on stroke rehabilitation [61] [53] [64] [63] [65] [5] [69]. Haptic based MI-BCI is promising for functional rehabilitation for stroke patients, as this training can be also applied to patients with no residual movement. The aim of BCI/NF is to stimulate neural plasticity in perilesional brain motor areas and support upper limb functional improvement. Since haptic BCI/NF based SMR achieve motor imagery with concurrent motor learning via kinaesthetic feedback, it is natural to think of rehabilitation for stroke patients even in a chronic condition. In these applications the question of the cortical target is still open. Usually the control of the orthosis is modulated by the ipsilesional side of the brain [75], contralateral to the affected hand, however, the ability to modulate perilesional activity is decreased with increased cortical damage [76]. For example,

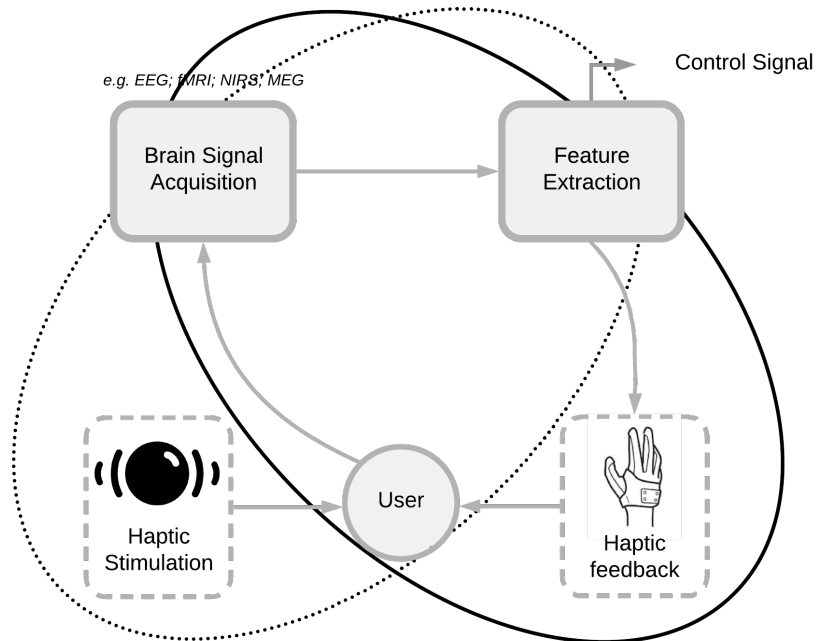


Fig. 4: Implementation of haptic feedback in aBCI or rBCI. In aBCI haptic interfaces provide the feedback from user's neural activity whereas in rBCI haptic interfaces provide a stimulation and the elicited brain activity is further decoded and transmitted as a command. aBCI loop (black circle) and rBCI (black dotted circle).

Bundy and colleagues [66] studied the contralateral motor area for the control of a portable exoskeleton, the assumption being that the recovery is optimal in the contralesional side and that functional improvements may be elicited [77]. In 2008, Buch and colleagues [64] demonstrated that chronic stroke patients with upper limb hemiplegia were able to control a magnetoencephalography (MEG) BCI by voluntarily modulating the ipsilesional SMR amplitude while receiving contingent haptic feedback with a hand orthosis. The haptic system used was a grounded mechanical orthosis attached to the plegic hand, one on each fingers except the thumb. The feedback was given in a passive way, with a movement of the orthosis elicited only if the modulation had reached a certain threshold at the end of the trial. Kinaesthetic feedback is mostly employed for stroke rehabilitation in agreement with the fact that rehabilitation outcomes of motor functions is more efficient with proprioceptive feedback. Most studies for rehabilitation imply kinaesthetic feedback but FES based-MI was also performed for patients. In an early case report from Pfurtscheller and colleagues, they applied non-invasive techniques to restore grasp functionality in a tetraplegic patient through FES [50]. This same method was applied with chronic stroke patients in [71]. The interested reader can find more

information about BCI applications for stroke rehabilitation in the review that Lopez-Larraz and colleagues [45] presented in 2018.

B. External Stimulation Paradigms

Brain signals can be elicited using external stimulation. Frequently used paradigms include SSEP as well as event-related potentials (ERPs). Most BCI using ERPs can be used without any prior training and do not have the phenomenon called "BCI-illiteracy" problem (i.e the BCI system fails to correctly detect the mental state of its user). The following paragraph will deal with external paradigms (P300 and SSSEP) and their relationship with haptic modality. To the best of our knowledge, contrary to SMR-based BCI/NF where haptic technologies are used to provide the feedback, in external stimulation paradigms haptic interfaces are mostly employed as a stimulus.

1) **P300:** P300 is a positive deflection of the EEG signal occurring around 300 ms after presentation of a given stimulus (visual, haptic or auditory). A major strength of this paradigm is its reproducibility and stability as a feature for rBCI [89]. The majority of P300-based BCI studies use the visual channel

TABLE II: P300 based haptic: K: Kinesthetic, H: Hand, W: Wrist, FF: Force Feedback F: Finger(s) P: Portable, G: Grounded, D: Discrete, C: Continuous, PP: Physical practice, *: MEG, T-Vib: Tactile vibrotactile, E-T: Electrotactile V: Visual, T: Thumbs, I, Index, M: Middle finger, NP: Number of patient, NS: Number of subjects, SP: Stroke patients, (C)LIS: (Complete) Locked-In Syndrome, FC: Feedback comparison, HI: haptic influence, HD: haptic design

Haptic sensation	Actuator technology	Portability	Multimodality	Haptic Gain	Paper Purpose	NP/NS	Reference
T-Vib	Mechanical vibrators H or W	P	V	Inf	Research FC	-/18	[78]
T-Vib	Mechanical vibrators (waist)	P	none	N/A	Research HD	-/10	[6]
T-Vib	Mechanical vibrator (L/R W)	P	none	N/A	Rehabilitation	11/- LIS	[79]
T-Vib	Mechanical vibrators (L/R W)	P	none	Sup in communication speed	Research FC (auditory and MI)	-/10	[80]
T-Vib	Mechanical vibrators (L/R W + shoulder)	P	none	N/A	Rehabilitation	12/- LIS/CLIS	[81]
T-Vib	Mechanical vibrators (4 on arm)	P	none	Sup	Rehabilitation/Research FC	1/- LIS	[82]
T-Vib	Mechanical vibrators (torso)	P	V	Bimodal = unimodal	Research	-/10	[4]
T-Vib	Mechanical vibrators (3 F)	P	Hex-O-Spell	Inf	Rehabilitation/Research FC	6/5 ALS	[83]
T-Vib	Mechanical vibrators (knees, abdomen and neck)	P	none	N/A	Research HD	-/10 elderly subjects	[84]
T-Vib	Mechanical vibrators (F)	G	Hex-O-Spell	=	Research HD FC	-/12	[85]
T-Vib	Mid-air stimulation	G	none	N/A	Research HD	-/13	[86]
T-Pressure	solenoids (F: I,M,R)	G	V	N/A	Research HD	-/5	[87]
K	H FF	G	none	N/A	Research HD	-/7	[88]

as stimulation: one of the motivations of using haptic for P300-based-BCI is indeed to reduce the dependence of the gaze in rBCI. The interest here is less to imitate a kinaesthetic or tactile sensation but rather to give the haptic stimulation in the most efficient way. Indeed, most of haptic-based P300 studies use tactile sensation as stimulation rather than kinaesthetic sensation. The first appearance of this paradigm in a haptic-based BCI study is from Aloise and colleagues [78], they investigated the influence of a tactile stimulus on classification performance in eight subjects. Tactile stimulus was provided with 8 vibrotactile stimulators placed at different positions on hands and wrists. They reported that tactile stimulus increased the latency of the principal P300 component (600ms peak after haptic stimulus against 400ms with the visual stimulus) and that online classification performance was weaker than with visual stimulus (68% against 93%). Other studies using vibrotactile factors in P300-based BCI followed, differing on the place where they vibrators were located: on the wrist, on the arm, on the palm, on the neck and even on the head [90] [91].

The presence of other forms of haptic interfaces in P300-based BCI studies is still marginal and further studies are required to assess if they have potential to enhance BCI efficiency. Kinaesthetic stimulation with force feedback has been investigated in [88] where the kinaesthetic sensation was delivered through a joystick to the subject's dominant hand and provided 4 different movements corresponding to the different directions. Hamada and colleagues [86] tested the first non-contact method for producing tactile sensation for BCI (mid-air haptics) while in [87] tactile pressure sensation was tested.

P300 paradigm requires less training and may achieve higher accuracy than MI paradigm [92] and has the potential to be used for the control of communication system for patients with Locked-in syndrome (LIS) or completely locked-in syndrome (CLIS). LIS or CLIS are conditions where the patient cannot communicate or have control on his motor function except for vertical eye movement and blinking [93]. BCI may open a new communication solution for these patients with sufficient intact cognitive abilities [94] [95]. It is in this perspective that Guger and colleagues compared these two paradigms to assess whether vibrotactile P300 outperformed MI in a communication system for LIS patients [81]. The use of haptic-based P300 for the control of an object of the everyday environment has also been studied, in particular for the control of wheelchair because the visual feedback limits the user interaction with the external environment [84]. Recently, a spelling application with the use of tactile stimulation on the finger tips was developed by Van der Waal et al. [85], with spelling rates resulting similar to visual spellers. Kaufmann and colleagues [96] described an experiment in which they tested healthy users steering a virtual wheelchair in a building. The four navigation directions were associated with different factor locations on the body. Out of the 15 participants, 11 successfully navigated a route along four waypoints supporting the view that haptic P300 paradigm have potential for medical applications.

2) *Steady-State Somatosensory Evoked Potential (SSSEP)*: SSSEP are a steady-state component of brain signals evoked

by sustained repetitive vibrotactile stimulation within the frequency range of (17-35 Hz) [102]. The idea behind the use of such method is to increase the information transfer rate (ITR) (which is slower with SMR-based paradigms because it requires some second to establish ERD patterns) without loading the eyes gaze [97]. SSSEP also represent an alternative to visual-based P300 or steady-state visual evoked potential (SSVEP). Because the stimuli paradigm is based on vibrations, most studies use tactile interfaces with a vibrator to deliver the stimulus. The first appearance of SSSEP within a haptic-based BCI environment is found in the study by Müller-Putz and colleagues [97], in which the authors investigated whether SSSEP is as efficient as BCI paradigm. Tactile stimulus was provided by vibrotactile stimulators placed on both indexes and the user had to concentrate on one stimulus (right or left). They reported that on four healthy subjects only half reached classification accuracy of 70%. The placement of the vibrotactile stimulators in SSSEP-based BCI differs between studies even if in most cases is concentrated on the hands of the user (fingers, wrist) or its feet [101], being the discrimination of different vibration frequencies higher when the factors are placed in these locations. Comparison between paradigms has also been investigated: for example, Severens and colleagues [103] studied the difference of performance between SSSEP and P300 reporting that P300 outperformed SSSEP and the combination of both did not result in better performance than P300 alone. These results show the limitation of this paradigm, the comfort of the subject being low (he has to concentrate on one of two or more tactile stimuli) [104], which is not the case with SSVEP where the eye position primarily determines the target [97]. The combination of SSSEP with other paradigms could be more promising. Ahn and colleagues [105] combined the SSSEP (left and right finger) with an imagined movement BCI paradigm. Kim and colleagues [101] designed a wheelchair driving system which provide three vibrotactile stimulators to control different directions indicating that this system has potential to help Amyotrophic Lateral Sclerosis (ALS) patients or other patients with LIS to gain independence in their daily activities.

IV. DISCUSSION AND PERSPECTIVES

Haptic-based BCI/NF applications have gained increasing interest in recent years. Researchers using haptic as to provide feedback or stimulation have focused on 3 different paradigms: (1) haptic-based SMR where kinaesthetic feedback is mostly employed and used for stroke rehabilitation, (2) haptic-based P300 where tactile stimuli are generally used to elicit a brain response for the control of an object and (3) haptic-based SSSEP where vibrotactile stimulus are employed. In each of the paradigms presented in this review, clinical applications have been tested with promising results. Nevertheless, there are limitations and challenges that must be addressed by the haptic-based BCI community. In this section, we will discuss some of these points regarding the design of haptic systems adapted to BCI, the utility and interest of haptic feedback for BCI and NF applications (with respect to other modalities) and limitations of current solutions.

TABLE III: Haptic based-SSSEP, P: Portable, G: Grounded, D: Discrete, C: Continuous, PP: Physical practice, *: MEG., V: Visual, T-Vib: Tactile Vibrotactile

Haptic sensa- tion	Actuator technology	Portability	Multimodality	Haptic Gain	Paper purpose	NP/NS	Reference
T-Vib	Mechanical vibrator (1 F)	P	none	N/A	Research	-/4	[97]
T-Vib	Mechanical vibrator	P	none	N/A	Research	-/14	[98]
T-Vib	Mechanical vibrator (W)	P	V (cue)	N/A	Research	-/57	[99]
T-Vib	Mechanical vibrator (2 F)	G	none	N/A	Research	-/16	[100]
T-Vib	Mechanical vibrator (L/R foot)	P	none	N/A	Research/Rehabilitation	-/5	[101]

Most of the BCI studies involving haptic have used the MI paradigm. This general trend is mostly explained by the fact that in MI task, closing the sensorimotor loop has potential to improve the quality and pertinence of the feedback provided, thus enhancing user engagement and NF performance. On the other hand, for SSSEP or P300 paradigms, haptic feedback is seen more as an alternative to the visual channel. Concerning the applications of haptic BCI/NF, this review indicates that there is a major tendency on using these systems for rehabilitation, especially for stroke patients, and that the vast majority of studies used a kinaesthetic feedback, with the rationale of reproducing a real and complex movement. On the other hand, tactile feedback is mainly used with the aim of restoring comfort for patients with LIS syndrome or patients with visual impairments, rather than for rehabilitation purposes. The majority of kinaesthetic feedback involves the upper limb with orthoses placed either on the hand or arm; this is not necessarily the case of tactile feedback that can be placed on different parts of the body. The visual modality is also commonly employed in these studies, either as a visual clue (i.e. to know if the user has to imagine a right or left movement), or as feedback complementary to the haptic feedback. The visual feedback metaphor is either classic (a bar or thermometer) or a more realistic proprioceptive feedback representing for instance a hand. The gain of the haptic with respect to the visual modality in different paradigms remains to be more accurately assessed, even though several studies have cleared the ground and seem converging on the fact that haptic is either equivalent or more effective than visual feedback from some applications.

Haptic-based P300 is mostly based on tactile vibration as a stimulus and rarely with other modalities. Visual stimuli is used together with haptic stimulation in P300 paradigm mainly to assess the gain of a haptic stimulus. The consensus around this gain is also still unclear because some studies show an equivalent effect on the classification performance while in others haptic-based paradigms have reduced performances with respect to visual ones. The use of a haptic stimulus is often motivated by the fact that haptic remains the only possible communication channel for some patients (LIS, CLIS) where the use of the visual channel is not always possible. Contrary to haptic-based SMR paradigms, for P300 applications there is a richer literature dealing specifically with the design of the haptic interface.

Applications based on haptic SSSEP are very similar to P300 paradigms but very limited research has been done on the design of such systems. Since P300 and SSSEP share similar objectives, it would also be interesting to compare these 2 paradigms in future studies.

A. Design of haptic based BCI/NF

The integration of haptics in BCI/NF environment can be complex and entails some challenges at different levels. This is also because haptic-based BCI/NF studies are usually designed by imitating visual feedback protocols, even if the design may be sub-optimal for the haptic modality. In the following section, we will address some issues that should be addressed

in the design of haptic BCI/NF protocols adapted to specific applications.

1) *When and how should the feedback be provided?:* The basis of human-computer interaction is the use of a feedback, which underlies the interaction phenomenon occurring between the user and the system [106]. A recurring question in the BCI community is the frequency at which the feedback is provided. The feedback can be given in two different ways: continuously or discretely. It would seem more natural in a BCI environment to give the feedback at the end of a successful trial than continuously. Conversely, in NF paradigm, the feedback is an indicator for the user of its own cerebral activity: here it would seem more appropriate to give haptic feedback in real time. A recent study from [107] indicated that improvement of MI task could appear if a vibrotactile stimulation of the non-dominant hand or the paretic hand for the patients is performed during MI, hence in real-time alerting on the importance of defining the feedback delivery modality depending on the desired application.

2) *Haptic interfaces Induced Artifacts:* In haptic BCI NF applications different artefacts can contaminate the signal; these artefacts can be generated by the devices controlled with the haptic feedback (i.e. noise generated by actuators based on electric/magnetic neurostimulation, on robotic devices [108] [71]) or have a physiological origin (i.e. compensatory movements, cranial and neck muscle activity, eye movements, swallowing, etc). The question of whether the haptic feedback introduces additional artefacts thus influencing BCI performance is still debated and highly depends on which haptic system has been tested. For tactile feedback, some studies showed that no interference with electric signal has been found [11] [109]. For example, Leeb and colleagues [71] demonstrated no significant difference during the rest and the stimulation with a vibrotactile feedback. However, Hommelsen and colleagues [110] showed that FES feedback was a considerable source of false positives when the mu rhythm was used for the detection of efferent commands. We suggest that a thorough study of the influence of haptic feedback, whether tactile or kinaesthetic, should be conducted to determine artefacts induced by vibratory feedback and feedback with an orthosis.

3) *Features extraction and feedback calculation:* According to recent findings from Bashashati et al. [111] the choice of the classifier for a BCI system depends on the feature extraction method used. We also suggest that the choice of the classifier and the choice of the feature must take in account the specific feedback modality employed, e.g. an optimal classifier for a haptic feedback may be not efficient for a visual feedback. The majority of EEG classification algorithms are developed for vision-based BCI/NF while neurophysiological responses to tactile stimuli may differ: a research effort in defining methodological framework specific to the analysis of haptic features is therefore needed.

4) *Haptic based BCI/NF vs haptic interfaces: a technological gap:* To date, the BCI community uses haptic interfaces for sensory feedback or as stimulation systems that are generally simple and sometimes dated. The haptic interfaces have hugely progressed in recent years and it would probably be interesting

to integrate these technological advancements into BCI/NF studies. If we consider for instance the DOF of such haptic devices, at present the majority of studies involving a kinaesthetic system are limited to only one DOF even if the device can provide more. Using more DOF may facilitate motor learning [112] and should be investigated for rehabilitation of stroke patients. For stroke rehabilitation, tactile or kinaesthetic devices already exist but not in a BCI environment, for example, Lin and colleagues [113] developed a haptic glove equipped with vibrotactile stimulators that interact with a virtual-reality environment. Other studies have focused more on the ergonomics of the user by designing exoskeletons with multiple DOF [114] [115]. However, the wearability is not often a priority while it must be taken in account to enable the user to optimally perceive and interact with the environment. For instance, In and colleagues [116] developed wearable hand interfaces, proposing a jointless hand exoskeleton weighting only 80 g. We suggest that portability of haptic feedback should be more central in future haptic studies design.

B. Haptic Vs other modalities

Visual feedback has historically dominated the field of BCI/NF and only in recent years other modalities to deliver information (auditory or haptic) have been explored [117].

1) *The gain of haptic*: The gain of haptic over the other modalities could be assessed looking at different parameters such as BCI/NF performance, comfort of the subject or its adaptation in a daily environment. For example, haptic feedback could enhance MI [107] by bypassing BCI-illiteracy. BCI-illiteracy represents a big challenge in BCI research [118] and currently available SMR-based BCI/NF may have reached the limitation of their performance, as approximately 30% of healthy subjects [119] and 40% of stroke patients [120] can not reach the critical BCI accuracy of 70%. The recent work from Lukyanov and colleagues [117] suggest that after some training, the type of feedback (visual or tactile) does not affect the classification accuracy. It impacts however the comfort of the subjects who describes the tactile feedback as more natural. Moreover, there are still few studies that compare different modalities: for SMR paradigms it seems that visual and haptic are comparable in terms of BCI performance, however, for P300-based studies this is still not clear. The gain of the haptic must also be determined with respect to the decrease of visual workload since the feedback no longer occupies the visual channel.

In current approaches haptic feedback is delivered in a uni-dimensional way e.g the task performed by the user is usually binary: open/close, open/grasp. For stroke rehabilitation it could be a limitation since the mental task is often more complex in reality. Future studies should explore the possibility to include more than one task in order to provide a more complex training (bearing in mind that this would also increase the training time). We suggest that more research should be done on the design of more realistic haptic training.

2) *Multimodality*: In our daily environment we are faced with many simultaneous and multimodal stimuli, it might therefore seem interesting to test a multisensory feedback approach in a BCI context. We can hypothesise that multimodal

feedback like visuohaptic or audiovisual feedback could be more effective than simple unimodal feedback [121]. In a clinical context it might also be interesting, i.e. vision can be compromised for LIS, CLIS or ALS patients and the use of additional sensory feedback might be a good alternative to uni-dimensional feedback. Several studies tested the impact of a multimodal visuo-auditory feedback for BCI-based SMR: overall the effect of a multimodal feedback is either similar to a visual unimodal feedback [122] or shows better results in the first session [3]. In some cases multimodal feedbacks could increase performance in some naive subjects [123]. For the visuohaptic modality, the investigation from Brower [6] showed that visual-tactile feedback has better performance over uni-sensory stimulation. It has also been suggested that the feedback given to the subject could either be equally shared on different channels, or replicated on each of them [1] or even dynamically distributed between channels. Although the use of visual feedback in addition to haptic feedback is often systematic, it is not always justified. This suggests that further work is needed to shed light on the use of multimodal feedback and to assess the interest of a visuo-haptic feedback compared to unimodal ones, whether visual or haptic.

V. CONCLUSION

Haptic interfaces are undergoing major technological progress and the BCI/NF community looks at the haptic modality with increasing interest. In this review we summarise and discuss state-of-the-art research on haptic-based BCI/NF. We outline different paradigms using haptic interfaces, such as SMR, P300 and SSSEP and methodologies for the design of pertinent haptic applications. We identify major trends in the use of haptic in BCI and NF and limitations of current solutions. To date there is no consensus on the effectiveness of haptic feedback for BCI and NF systems. This review shows that haptic interfaces have potential to enhance performance and increase the pertinence of feedback provided, in particular for SMR paradigm used in the context of motor rehabilitation. Further studies are however required to test the use of innovative haptic technologies for BCI and NF and assess the utility of haptic, used alone or in combination with other modalities.

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