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REVIEW

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Differentiation among bio- and augmented- feedback in technologically assisted rehabilitation

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ABSTRACT

Introduction: In rehabilitation practice, the term 'feedback' is often improperly used, with augmented feedback and biofeedback frequently confused, especially when referring to the human-machine interaction during technologically assisted training. The absence of a clear differentiation between these categories represents an unmet need for rehabilitation, emphasized by the advent of new technologies making extensive use of video feedback, exergame, and virtual reality.

Area covered: In this review we tried to present scientific knowledge about feedback, biofeedback, augmented feedback and neurofeedback, and related differences in rehabilitation settings, for a more proper use of this terminology. Despite the continuous expansion of the field, few researches clarify the differences among these terms. This scoping review was conducted through the searching of current literature up to May 2020, using following databases: PUBMED, EMBASE and Web of Science. After literature search a classification system, distinguishing feedback, augmented feedback, and biofeedback, was applied.

Expert opinion: There is a need for clear definitions of feedback, biofeedback, augmented feedback, and neurofeedback in rehabilitation, especially in the technologically assisted one based on human-machine interaction. In fact, the fast development of new technologies requires to be based on solid concepts and on a common terminology shared among bioengineers and clinicians.

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Sensorimotor learning; feedback; augmented feedback; biofeedback; rehabilitation; motor control; neuroplasticity

1. Introduction

In the past decades, an increasing number of devices, robots, and sensor-based technology has been approved and commercialized as medical devices for rehabilitation [1]. This represents a step over in particular in the field of neurological rehabilitation because these technologies can boost several aspects involved in the harnessing neuroplasticity-dependent recovery [2]: i) increased feasibility of task-oriented training in particular for more impaired subjects [3]; ii) a more engaging therapy thanks to exergames, virtual reality, and augmented reality feedback [4]; iii) augmented interactions between brain and distal motor action (feedback – feed-forward motor control) [5,6].

Accordingly, neurorehabilitation is now more focused on a multimodal process to facilitate motor deficit recovery in multimedia environment through exergaming, videogame feedback, and virtual reality to engage subjects in meaningful real-time and task-related visual or audio feedback [4].

It is out of doubt that feedback is a key component in motor control [7], and hence involved in motor and cognitive rehabilitation [8].

First of all, feedback can be considered as the return of a portion of the outcome from a system to its input [9], providing 'information about what was done' [7]. Biofeedback is the feedback of biological signals used to enable a person to identify and modify a bodily function of which they are usually unaware [10,11]. A particular type of biofeedback is neurofeedback, a biofeedback related to a brain signal [12].

Skilled motor behavior involves different control modes which rely on sensory feedback in which a desired state is the input for movement control, the real state is measured by sensory systems and compared with the desired state: their difference can be considered as a gap to fill, a distance to travel, or an error to correct [13], as in Figure 1.

In rehabilitation, the measure of this error can be verbalized by the therapist, augmenting the sensorimotor feedback of the patient [7]. Nowadays, thanks to the new technological devices developed for rehabilitation, the augmentation of a physiological feedback can be provided by the machine according to a top-down approach of neurorehabilitation [1]. This approach is followed also by the biofeedback technique

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already developed in Seventies, but not related to augmenting a feedback already consciously perceived by the patient [14].

Thus, feedback is a key component of sensorimotor control and a wide range of feedbacks can be used with the aim to boost neuroplasticity in motor and cognitive rehabilitation [8], whereas the term biofeedback assumed the meaning of a specific approach, a specific kind of therapy, used to modulate a body function and thus a motor behavior [10]. Indeed, the influence of the different types of feedback on movement control performance and motor learning is of primary interest in neurorehabilitation.

However, the spreading of the rehabilitative devices including feedback or biofeedback has led to some areas of overlapping on what feedback, augmented feedback, biofeedback, neurofeedback, performance feedback mean in rehabilitation and for what they can be used for.

In light of these considerations, the aim of the present study is to provide a scoping review related to the rehabilitative technological devices and the therapeutic and technological aspects of defining feedback, augmented feedback and biofeedback/neurofeedback, the discrepancies in the uses of these terms and the overlapping areas in rehabilitative neuromotor context.

2. Methods

This scoping review on the role and definition of feedback in rehabilitation was conducted through the searching of current literature up to 31 May 2020, using following databases: PUBMED, EMBASE and Web of Science. The search strategy used for a comprehensive search was as follows: ('Feedback' OR 'Biofeedback' OR 'Neurofeedback' OR 'Videofeedback' OR 'Audiofeedback') AND ('Rehabilitation' OR 'Exercise' OR 'Motor Recovery'). Because 'haptic feedback' is written as two distinct words, the studies related to this type of feedback entered into this review because already included in those with the keyword 'feedback'.

2.1. Inclusion and exclusion criteria

Clinical studies of motor rehabilitation using feedback and biofeedback were included. The definitions of feedback and biofeedback are reported as mentioned by authors and analyzed. Articles published up to 31 May 2020 were considered for inclusion.

3. Results of the literature search

Although the diffusion of devices and technique providing feedback and biofeedback is high, actually there is not clinical information to distinguish them in a useful manner to better integrate feedback or biofeedback in individualized rehabilitation program. Table 1 shows some examples of different fields and outcomes considered in literature for feedback and biofeedback use in rehabilitation, explicating the feedback definition considered by authors, when available, and input/output signals.

Table 1 already summarizes among papers at least three main problems. Firstly, the biofeedback (or feedback) have been defined in some papers on the basis of the type of output that returns as input to the system (e.g. 'EMG-biofeedback' refers to the signal extracted by muscular activity [15–19]), whereas in others on the basis of the modality of this return (e.g. visual biofeedback [20] or auditory biofeedback [21] or audiovisual feedback in virtual reality [22,23]). For example, the expression 'EMG-biofeedback' usually refers to the type of measured signal (electrical muscular activity) [15–19], whereas the expression 'visual biofeedback' usually refers to the modality with which the subject received the information about the measured signal (that is not something related to the visual system) [20,24].

The second aspect is the absence of a clear definition of the differences between feedback and biofeedback in rehabilitation. For example, the visual feedback used by Bell and colleagues [25] refers to the knee joint flexion measured in real time and showed on a monitor to the subject, also measuring the relevant range of motion (ROM). First of all, ROM is not a parameter measurable in real time, because it is the result of a complete movement and not an instantaneous value of a measured signal. Hence there is an important difference between joint angle feedback and joint ROM feedback. Furthermore, the visual feedback about the knee joint could be easily observed by patient looking his/her knee, so it seems more proper to define it as an 'augmented feedback'. In other studies, the feedback is related to a performance not easily referring to a single physiological signal. For example, in Maggio and colleagues [26], the patient has to identify and select a specific target (based on colors, type of image, shape, and so on), neglecting some distractors, receiving an 'immediate audio and video feedback, observed in the virtual environment'. This type of feedback is related to the performance of the subject, also involving cognitive functions, and it is not just related to a single signal measured in real-time. Can we call it biofeedback?

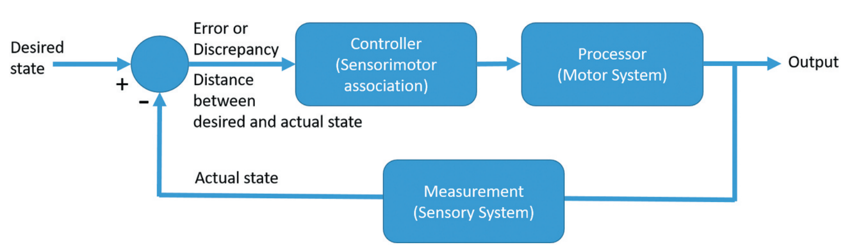

Figure 1. Feedback and skilled motor control.

Table 1. Examples of different fields and outcomes considered for feedback and biofeedback use in rehabilitation.

Authors and year	Title	Keywords	Population	Feedback definition	Input of the device (Measured signal)	Output of the device
Intiso D et al, 1994 [15]	Rehabilitation of walking with **electromyographic biofeedback** in foot-drop after stroke	Electromyography, gait, rehabilitation	Stroke patients	"continuous, direct, and objective communication of information between patient and physiotherapist regarding the recovery of deficit."	EMG	Acoustic
Yoo JW et al., 2017 [16]	Augmented effects of **EMG biofeedback** interfaced with virtual reality on neuromuscular control and movement coordination during reaching in children with cerebral palsy	Arm swing movement, central pattern generator, cerebral palsy, gait training, muscle activity	children with spastic cerebral palsy	Not available	EMG	real-time audiovisual sensory output
Dursun N et al., 2001 [17]	**Electromyographic biofeedback**–controlled exercise versus conservative care for patellofemoral pain syndrome	Electromyography; Leg; Pain; Pain measurement; Rehabilitation	Patients with patellofemoral pain syndrome	"a training procedure that could be used during quadriceps exercises to equalize vastus medialis and vastus lateralis muscle activity"	EMG	auditory feedback
Akkaya et al. 2012 [18]	Efficacy of **electromyographic biofeedback** and electrical stimulation following arthroscopic partial meniscectomy: a randomized controlled trial	Meniscectomy, rehabilitation, electromyographic biofeedback, electrical stimulation	arthroscopic partial meniscectomy	"a method which allows retraining of the muscle by creating new feedback systems as a result of the conversion of myoelectrical signals in the muscle into visual and auditory signals"	EMG	visual and auditory signals
Bloom et al. 2010 [19]	Prolonged **electromyogram biofeedback** improves upper extremity function in children with cerebral palsy	electromyography, biofeedback, cerebral palsy, upper extremity	children with cerebral palsy	Not available	EMG	Vibration
Van K et al., 2006 [20]	The use of real-time ultrasound imaging for **biofeedback** of lumbar multifidus muscle contraction in healthy subjects	lumbar spine, motor learning, sonography, stabilization, trunk exercises	Healthy subjects	Not available	Real-time ultrasound	visual biofeedback
Fino PC et al. 2017 [21]	Assessment and rehabilitation of central sensory impairments for balance in mTBI using **auditory biofeedback**: a randomized clinical trial.	Sensorimotor integration, mTBI, Concussion, Balance, Gait, Biofeedback	Mild traumatic brain injury (mTBI) with non-resolving complaints of balance	Not available	Linear accelerations near the body center of mass (by a lumbar-mounted smartphone)	Auditory feedback
Duffell LD et al. 2019 [27]	The effects of FES cycling combined with **virtual reality racing biofeedback** on voluntary function after incomplete SCI: a pilot study.	Biofeedback, Cycling, Functional electrical stimulation, ISNC-SCI motor score, Spinal cord injury, Virtual reality	sub-acute and chronic patients with incomplete spinal cord injury	Not available	Crankshaft torque	Virtual avatar (visual)
Morone G. et al. 2014 [52]	The efficacy of balance training with **video game-based therapy** in subacute stroke patients: a randomized controlled trial.	Not available	subacute stroke adult patients	Not available	Postural sway	video game-based visual feedback
Booth AT et al. 2019 [22]	Effects of **Immersive Biofeedback** on Gait in Children with Cerebral Palsy.	Biofeedback, psychology; Cerebral palsy; Rehabilitation; Virtual reality; Walking	children with cerebral palsy	Not available	Gait analysis	Avatar-based visual feedback
Yip SL, & Ng GY, 2006 [64]	**Biofeedback** supplementation to physiotherapy exercise programme for rehabilitation of patellofemoral pain syndrome: a randomized controlled pilot study	Not available	Patients with patellofemoral pain syndrome	Not available	EMG	Visual feedback
Asmaa Abd El Rhman Ahmed, et al. 2019 [65]	Influence of **Biofeedback** and Task Oriented Training on Hand Skills in Children with Spastic Cerebral Palsy	Biofeedback, hand function, task oriented training, cerebral palsy, occupational therapy, wrist extension	children with spastic cerebral palsy	"a self-regulation technique through which patients learn to voluntary control what were once thought to be involuntary body processes"	EMG	Visual feedback

(*Continued*)

Table 1. (Continued).

Authors and year	Title	Keywords	Population	Feedback definition	Input of the device (Measured signal)	Output of the device
Bortone I et al. 2018 [23]	Wearable **haptics and immersive virtual reality** rehabilitation training in children with neuromotor impairments	Assistive technologies, serious games, virtual reality, wearable robotics, haptic devices, children with neuromotor impairments	Children with neuromotor impairments	Not available	Kinematics	Haptic and immersive audiovisual feedback
Calabrò et al., 2017 [24]	The role of **virtual reality** in improving motor performance as revealed by EEG: a randomized clinical trial	Lokomat, Ersp, Loreta, Mirror neuron system, Virtual reality	Stroke patients	Not available	Joint movements	Visual and acoustic feedback
Maggio et al., 2018 [26]	What About the Role of **Virtual Reality** in Parkinson Disease's Cognitive Rehabilitation? Preliminary Findings From a Randomized Clinical Trial	virtual reality training, Parkinson disease, cognitive rehabilitation	Patients with Parkinson disease	Not available	Body movements performing specific tasks	real-time augmented and multi-sensory feedback
Bell et al., 2019 [25]	Verification of a Portable **Motion Tracking System** for Remote Management of Physical Rehabilitation of the Knee	knee; rehabilitation; physical therapy; mobile health; mHealth; inertial measurement units	Patients with knee injury or surgery	Not available	Knee joint position and knee range of motion	visual feedback

Finally, many different technologies (including among others: robots [24], virtual reality [16,22,26], electrical stimulation [18,27], smartphones [21]) have been used in different modalities: in real-time [18,20] or based on the achievement of a threshold value [21] or on objective of the task [16,23,24].

All these aspects open some questions. Should we refer the feedback to the measured signal or to the modality of its presentation on the subject? When should we use the term biofeedback and when the term feedback if both referring to biological signals? Can we use the term 'augmented feedback' only if subjects already have some natural accesses to their body signals by proprioception, vision, tactile signals, and so on?

3.1. Feedback

The literature searches on the concept of feedback revealed a long story and a wide use of this term in many fields of science. To briefly retrace the history of feedback concept through the papers found in this review could help to clarify the evolution of this concept from engineering to medicine and finally to medical engineering. The concept of feedback was introduced in electronics in 1920, defined as: 'the return of a fraction of the output signal from one stage of a circuit to the input of the same or a preceding stage, tending to increase or decrease the amplification'. A social science definition of feedback was proposed in 1943 and stated that the behavior of an input is controlled by the margin of error at which the object stands at a given time with reference to a relatively specific goal (output) [28].

Signals returning to the brain about the state of organs are natural feedbacks, and then brain can use them for controlling organs. This control could happen in an automatic way, a semi-automatic or needing a voluntary conscious choice. For example, the increase in running speed for taking a bus is a voluntary choice following the visual feedback of the distance between the subject and the bus, whereas the consequent increment of heart beat frequency is an automatic adjustment following the increase in running speed. Also sensorimotor learning could happen in an implicit or an explicit manner [28]. Most of feedbacks provided to the subject by a technological device are related to the subject conscious interpretation when instructed on how to interpret the dimensions and modalities (visual, auditory, haptic, body segments posture) of the feedback. But it may also be guided by a body signal that per sè could be or not a signal analyzed by brain at conscious level, i.e. with the awareness of the subject. For example, a visual feedback could be related to a joint angle or to blood pressure: in both cases the brain is aware of them, but in the latter the subject is often not aware.

Rehabilitation training could be facilitated more implicitly, for example, when a physiotherapist would gradually adapt an environment, thus facilitating the motor skills without verbal instructions. Often multiple learning strategies are used within one training session [29], representing an implicit-explicit continuum [30]. In explicit strategies, the influence of the different types of feedback on movement control performance and motor learning is challenging.

However, there always have been some overlapping areas among types of feedback, despite the need to determine general conceptual formulations of the terms feedback different approaches have been stated through years since 1908 [14,31].

In general, we could say that feedback is the return of the outcome (or a portion of that) of a system to its input for modifying its next state. The system could be the human sensorimotor control as well as to a machine control. It could be in real time, if provided during the execution of movements to modify the next step of this execution, or given after the end of the movement to modify the next execution. Biofeedback, augmented feedback, and neurofeedback are three types of real-time feedback. Conversely, the feedback provided at the end of task execution can be called as performance feedback. It should be mentioned that human sensorimotor system works also using feedforward control, predicting the next state. These aspects are out of the scope of this review and they were well treated by Wolpert and colleagues [13,32,33].

3.2. Biofeedback

The biofeedback methods used in rehabilitation are based on measurements of the physiological systems of the body, such as biomechanical and physiological measurements. Biofeedback has been used for more than 50 years in rehabilitation. Experts suggest that the field began to take shape in the United States of America in the 1950s with related health sciences such as physiology, psychology, and instrumentation engineering. Biofeedback aims to unite mind and body to make mind conscious of body information in many forms, available relying on using instruments, so that mind learns to control the measured body's signals with exercise. Various reports described the application of biofeedback techniques in the treatment of numerous disorders through the neuromuscular system, electromyography (EMG) biofeedback, or a real-time ultrasound imaging biofeedback to facilitate normal patterns after injuries since 1950 [34].

Biomechanical and physiological parameters measurements of the body are principally important in biofeedback methods used in physical rehabilitation, and the correct set up and use of the biofeedback, combining both physical and mental conditions in patients with brain injuries and cognitive deficit, is a challenging component of a comprehensive rehabilitation program.

The clinical application of biofeedback rehabilitation protocol in patients with motor deficit begins by reeducating sensory motor system. Motor control reeducation in patients with motor control deficit improves control by applying biofeedback therapy through visual or audio feedback of electromyography (EMG), positional or force parameters in real time [35,36]. The neurological mechanisms underlying the effectiveness of biofeedback are unclear, but overall it could be the result of neuronal plasticity improvement by engaging auxiliary sensory inputs, thus making it a plausible tool for neurorehabilitation [37]. However, the effectiveness of biofeedback therapy could be influenced by size and site of brain lesions, furthermore patient's motivation and cognitive ability during therapy have an important impact on usefulness of therapy [8,37].

Biofeedback applications have been used for their potential in neurological disorders during rehabilitation for different purpose [37–41]. Other clinical studies using biofeedback techniques to reduce anxiety and other physiological disorders like Headache, Attention deficit (ADD) & hyperactivity (ADHD) disorder, hypertension and a variety of neuromuscular disorders are reported by Yucha & Gilbert [42].

In general, the term 'biofeedback' should be strictly connected to its history. For this reason, it is too much generic to define biofeedback as every feedback related to a biological signal. Conversely, because it was developed to make mind conscious of body information to train the subject in controlling the measured body's signals with exercises, the term biofeedback should be intended as

a feedback of biological signals used to enable a person to identify and modify a bodily function of which they are usually and/or partially unaware.

3.3. Neurofeedback

More recently, the use of real-time feedback on neurophysiological signals was introduced under the name of 'neurofeedback'.

Neurofeedback is a special field within biofeedback which devotes itself to training control over electro-chemical process in the human brain, to promote brain electrical activity changes in near real time, by presenting of quantitative electro-encephalographic (EEG) results to show the trainee current electrical patterns in patient's cortex [43]. For example, it was found to be effective in the neurorehabilitation of patients with stroke [43] and in the management of chronic pain [44].

Cognitive rehabilitation therapy traditionally used to treat muscular impairment via electromyography biofeedback has taken on a new form as neurofeedback therapy, which targets the brain and cognitive-motor functions through the use of EEG [45]. It devotes itself to training control over electrochemical processes in the human brain [42], and to stimulate the brain neuroplasticity. Therefore, neurofeedback therapy protocols are highly specific rehabilitation tailored techniques to retrieve cognitive impairments and varied within each study in patients with cognitive deficit following stroke.

Neurofeedback is a kind of biofeedback, which teaches self-control of neural functions to subjects by measuring neural activity and providing a feedback signal. Given the difficulties in measuring nerve activity, most of neurofeedback systems are based on the measures of brain waves to provide an audio or video feedback, giving positive or negative feedback for desirable or undesirable brain activities, respectively [46,47].

3.4. Augmented feedback

Given the proposed definition of biofeedback to refer to signals about which the subject is usually and/or partially unaware, there is the need to find a terminology for feedback referring to signals of which the subject is already completely aware, but with the aim to improve the attention of the subject on this signal. Again, it is important to highlight that the above definition of biofeedback was strictly related to the original meaning provided to this term [10,11]. To use the term biofeedback with respect to a feedback related to biological signal of which the subject is completely aware is not improper, but it is not in line with the literature referring to this term. A feedback given by a device but already measured by the subject and of which the subject is already directly aware can be called 'augmented feedback'. An example can help to better differentiate it by biofeedback. A subject flexing his/her knee has a direct perception of the movement and of the joint angular position thanks to his/her proprioception. A visual or acoustic feedback provided about joint angular position is an augmented feedback. Conversely, a feedback about the electrical activity of rectus femoris during the same movement should be called as biofeedback because the subject is not completely aware of the entity of the electrical activity of that specific muscle during knee flexion.

3.5. The overlapping terms in rehabilitation with devices

In the recent years, there was a rapid development of devices and related motor rehabilitation techniques providing several feedbacks, augmented feedback, or biofeedback with different aims. This was particularly emphasized for balance training and arm sensorimotor training [1]. In this scenario there is the possibility that different stakeholders call the instruments differently, sometimes for convenience, generating confusion and overlapping of terms. For example, recent reviews/research article in which the term biofeedback is used even for non-medical equipment as a home video game console [38,48,49]. Noteworthy, the Cochrane group included studies using this kind of consoles, naming them as non-immersive virtual reality [50]. In this case the correct name of these techniques applied for medical purposes should be 'exergame' or 'serious game' and the body information provided through the video is a feedback as correctly stated for example in the study of Hung and colleagues [51].

To differentiate between feedback and biofeedback applied to devices, it is important to consider the purpose for which the information is used: if a body movement is used to consciously control an exergaming (i.e. gaming device/console), a robot, or a sensorized device the correct term to be used is feedback. Whereas, if the information is used to control a motor behavior indicating what is correct for this purpose because the patient was otherwise not aware, it should be called biofeedback.

For example, the training of the balance ability could be performed through a commercial console (balance force platform with feedback related to game control) [52], with wearable devices [53], or a medical device (balance force platform with biofeedback related to postural control) [54].

Another example is the training of the arm through a sensorized device with a video-feedback [55] (feedback need to control the device with indirect implication on motor behavior) or with a EMG-biofeedback [17] (the information is directly implied to motor behavior modification).

In accordance with the presented theory Piggott et al. [56] reviewed the state-of-art on robotic devices for the upper limb, and benefits of including haptic feedback and virtual reality feedback during neurorehabilitation; defining its feedback and not biofeedback.

3.6. The types of feedback in sensorimotor learning and rehabilitation

A control system based on feedback could work online or offline. Online feedback highlights an error during the execution of a motor or cognitive task. An index of the global performance, for example a score achieved after a session of video-game-based therapy, can be considered as an offline feedback, usable to improve the following task (not the current one), modifying the strategy or adjusting some parameters in the motor control. These types of learning may influence the development of some strategies based on feedforward control, a predictive strategy based on the information previously acquired [32].

Feedbacks can be categorized also by the entity of their delay. All feedbacks have a delay, even those of sensorimotor control, often of few hundreds of milliseconds. For this reason, motor control exploits predictions of feedforward models [32]. Exteroceptive and proprioceptive signals contribute to the perception that can, in turn, be used as a predictive coding in which action can be seen as a discharge of motor neurons to cancel prediction errors through reflex arcs. In this scenario, perception could reduce perception errors by changing predictions, while action may reduce prediction errors by changing sensation, using top-down corticospinal projections not only as motor command per se, but as predictions about proprioceptive or kinesthetic sensations, according to active inference theory [57].

In fact, feedbacks could be related to both exteroceptive and also interoceptive signals. Visual, auditory, tactile signals are an example of exteroceptive feedbacks, whereas proprioceptive signals of interoceptive signals. Active inference suggests that attention should not be limited to the optimal biasing of perceptual signals in the exteroceptive domain but should also bias proprioceptive signals during movement [58].

Feedbacks could be negative, positive or neutral [33]. A negative feedback provides information of a subject error and it is mainly related to the error-based learning. A positive feedback highlights when a subject achieved the objective of the administered task, and it is more related to the reward brain networks. It is unclear, in these networks, the potential role of dopamine: some studies suggested that phasic dopamine signaling encodes prediction errors, some others reported that dopamine is not necessary for learning, a divergent dichotomy that could be overcome by the hypothesis that dopamine depletion impairs performance but spares learning, while the excitation of dopamine neurons drives reward learning [59].

A neutral feedback just provides information on the movements of the subject, increasing the awareness of the subject. Feedback can be also modulated in intensity, for example a negative feedback could be more intensive for greater error, or for longer time spent to complete the task, or for wide variable movement or for poor optimization of the task solution.

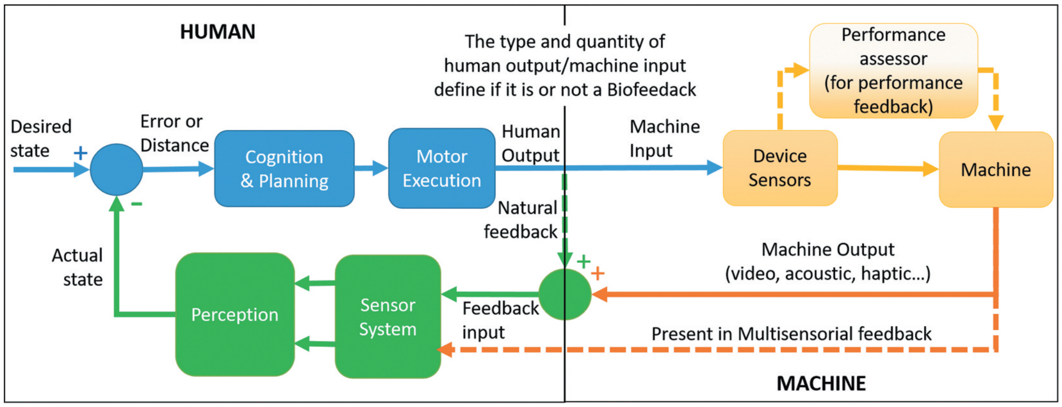

Figure 2. The human-machine feedback loop.

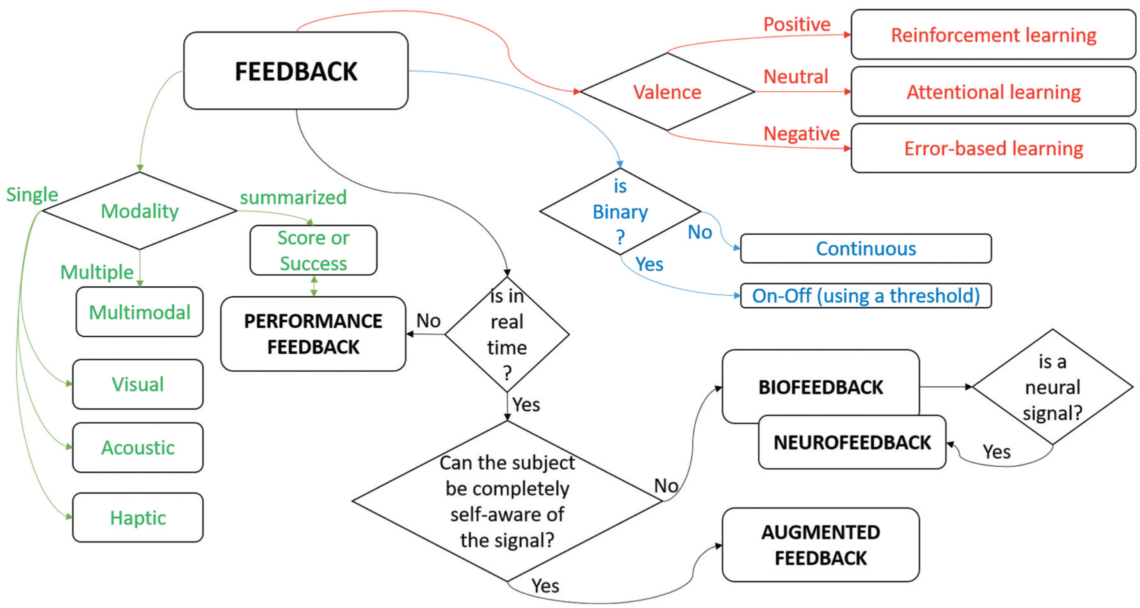

Figure 3. A visual snapshot of possible types of feedback, their modality, and their valence.

Feedback can be acquired from different motor outputs and may provide different sensory inputs. Feedback is mainly provided by technological devices with a visual stimulus on a monitor, or with an auditory stimulus, less frequently it is also related to a haptic stimulus, such as a vibration [60]. The above sensory modalities could also be combined in multimodal feedback [61]. About motor output, Tamburella and colleagues [62], for example, showed as when muscular-based information is used, a more direct effect on lower limb spasticity and muscle activity of subject with stroke is evidenced, but, when the feedback is based on joint torque, higher compliance in terms of force exerted is achieved.

Finally, sensorimotor feedback could be associate to three different types of learning [63]: sensor-perceptual learning (in this case feedback may favor a better perception of the stimuli and a wider comprehension of the task), sensorimotor associative learning (in this case feedback may favor a more optimal extraction of information relevant for the task execution, for example using selective attention), motor skill learning (in this case feedback may increase only the motor aspects, for example in biofeedback related to muscle activations).

4. Expert opinion

Figure 2 shows an extension of the feedback loop reported in Figure 1 to the human-machine interaction occurring during technologically assisted rehabilitation. In general, the feedback provided by a machine could be available during therapy for patients and also for physiotherapists, representing a key factor to improve exercise/task execution performances (and thus training performances). The feedback can act on sensorimotor and cognitive learning of the patient on the basis of different mechanisms: error-based learning, reinforcement learning, action-observation learning. So, the term feedback is, on the one hand, very general, but on the other hand it is very specific for defining how the sensorimotor system of a subject may learn (or re-learn) the ability of performing an action. In Figure 2, the green loop represents the feedback received by a subject.

In literature, the term 'biofeedback' is often used for indicating a specific rehabilitative technique and not generically as a biological feedback [10,11]. In the context of motor recovery, the biofeedback is considered as a rehabilitative technique increasing the capacity of sensing and controlling a bodily function and thus modifying a motor behavior. Figure 2 can represent a biofeedback if the human output is a body signal of which the subject is not completely aware and does not refer to the overall performance of the subject (such as the range of movement that is a parameter summarizing a performance and not measurable in real time). According to this Figure, if a natural feedback is present (represented by the dotted green arrow) the subject is already measuring his/her output thanks to his/her sensory system: in this case the machine is providing an augmented feedback. If the device provides multiple input to the human sensory system, we can talk about multisensory feedback. Finally, if the output of the machine is not related to one of more body functions, but to the entire performance of the subject, we need to refer to performance feedback.

Augmented multisensory feedback will be more and more commonly used due to the widespread diffusion of advanced technology assisted physiotherapy and occupational therapy. A correct definition of biofeedback should be based on the biological signal that is acquired and on the clear interpretation of the device output that will be the new input for a subject to improve his/her motor behavior. Indeed, firstly, we have to be sure that we are obtaining a measure congruent with the function we are addressing. Then, the devices should provide a biofeedback easily understandable by the patient, who needs to know if he/she is executing the required task in the correct or incorrect manner, but this definition of correctness should be based on strong scientific foundations.

Finally, this information should be used to modify motor behavior, allowing patient to voluntary control that function (operative conditioning). In this context, there will still be overlapping area, related to the fact that the same body information could result as a feedback or biofeedback depending on the purpose which it is used for (i.e. control a device or directly control a motor behavior).

We tried to resume in Table 2 the different types of feedback, proposing a clarifying definition, with details and examples. In Figure 3 we have also reported the types of feedback in relationship to its different features.

At the light of our review, a great confusion emerged by the definition of feedback, augmented feedback, and biofeedback related to neuromotor rehabilitation, especially when performed with a device and more effort should be done in the future to obtain a common classification of these terms shared among all stakeholders and end-users (physiotherapist, occupational therapist, bioengineer and clinician, patients) from one side and medical rehabilitative devices manufacturers and sellers from the other side. This will imply a growth of the research and their potential translational application in the clinical context. More clinical research in the field is necessary to better identify underlying mechanism for the different feedback and biofeedback learning processes and an agreement is needed between clinicians and researchers in the field regarding the rehabilitative and the technological contents. To improve the knowledge in this field will be more and more important in telerehabilitation and home rehabilitation for those patients working without any assistance by the physiotherapist and for whom the feedback provided could represent a remarkable component of the rehabilitation [66].

Table 2. The definition of different types of feedback in technologically assisted neurorehabilitation.

Type of feedback	Definition	Details	Examples
Feedback	The return of a portion of the outcome of a system (in our case a human) to its input for modifying its next state	It could be natural or artificial, it could be in real-time or postponed, proportional to the signal or related to the achievement of a threshold	The physiotherapist verbally correcting the subject during or the execution of a task or a video-game in which information about the current state is given to subject for correcting the next state
Augmented feedback	A feedback given by a device but already measured by the subject and of which the subject is directly aware	It could be given to the subject in the same modality of his/her natural feedback or not (visual, acoustic, haptic …)	Joint position feedback measured by an electrogoniometer and showed on a screen
Biofeedback	A feedback of biological signals used to enable a person to identify and modify a bodily function of which they are usually and/or partially unaware	It could be real-time, providing a continuous feedback or on-off if related to a threshold with the aim to modify motor behavior	EMG-biofeedback in which the information of electrical muscular activity was given to the subject in visual or acoustic modality
Neurofeedback	A biofeedback related to neural signals	It could be real-time, providing a continuous feedback or on-off if related to a threshold, or it could be related to a performance	EEG-biofeedback
Multisensory feedback	A feedback provided to the subject using multiple sensory channels	It could be combined with other type of feedback, but the output of the device is the input for different sensory systems of the subject	Video-games and virtual reality providing visual and acoustic feedback to the subject
Performance feedback	An information returned to the subject about what he/she has done at the end of a task for correcting the behavior in the next trial	It is given at the end of the task execution, so it does not act on the current trial, but on the next one	Scores given in video-games and virtual reality

Starting from the exposed issues, in the next years there should be a definition of standards of signal accuracy, a finalistic interpretation of biofeedback, and clinical application of operative conditioning.

These steps are not simple to be defined, so they should be achieved through a position paper or a national/international consensus conference involving all the main characters of this process.

Declaration of interest

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References

Papers of special note have been highlighted as either of interest (•) or of considerable interest (••) to readers.

1. Morone G, Spitoni GF, De Bartolo D, et al. Rehabilitative devices for a top-down approach. Expert Rev Med Devices. 2019;16(3):187–195.
2. Wolpaw JR. Harnessing neuroplasticity for clinical applications. Brain. 2012;135(Pt4):e215.
3. Boffa G, Tacchino A, Sbragia E, et al. Preserved brain functional plasticity after upper limb task-oriented rehabilitation in progressive multiple sclerosis. Eur J Neurol. 2020;27(1):77–84.
4. Tieri G, Morone G, Paolucci S, et al. Virtual reality in cognitive and motor rehabilitation: facts, fiction and fallacies. Expert Rev Med Devices. 2018;15(2):107–117.
5. Lotze M, Ladda AM, Stephan KM. Cerebral plasticity as the basis for upper limb recovery following brain damage. Neurosci Biobehav Rev. 2019;99:49–58.
6. Péran P, Nemmi F, Dutilleul C, et al. Neuroplasticity and brain reorganization associated with positive outcomes of multidisciplinary rehabilitation in progressive multiple sclerosis: a fMRI study. Mult Scler Relat Disord. 2020;42:102127.
7. Schmidt RA, Lee TD. Motor control and learning: a behavioral emphasis. Vol. 3. US: Human Kinetics; 1999.
8. De Bartolo D, Spitoni GF, Iosa M, et al. From movement to thought and back: a review on the role of cognitive factors influencing technological neurorehabilitation. Funct Neurol. 2019;34(3):131–144.
9. Simpson JA, Weiner ESC. The Oxford English dictionary. la University of Michigan: Oxford University Press; 1989. 2(5).
10. Beatty J, Legewie H, Editor. Biofeedback and behavior. Boston, MA: Springer Boston Springer; 1977.
11. Olton DS, Noonberg AR. Biofeedback: clinical applications in behavioral medicine. Englewood Cliffs, New Jersey: Prentice Hall; 1980.
12. Hammond DC. What is neurofeedback? J Neurother. 2017;10(4):25–36.
13. Wolpert DM, Flanagan JR. Motor prediction. Curr Biol. 2001;18(18):11.
14. Peper E, Shaffer F. Biofeedback history: an alternative view. Biofeedback. 2010;38(4):142–147.•• **An important review on classifications of different types of biofeedback and current biofeedback application being used in physical rehabilitation.**
15. Intiso D, Santilli V, Grasso MG, et al. Rehabilitation of walking with electromyographic biofeedback in foot-drop after stroke. Stroke. 1994;25(6):1189–1192.
16. Yoo JW, Lee DR, Cha YJ, et al. Augmented effects of EMG biofeedback interfaced with virtual reality on neuromuscular control and movement coordination during reaching in children with cerebral palsy. NeuroRehabilitation. 2017;40(2):175–185.
17. Dursun N, Dursun E, Kiliç Z. Electromyographic biofeedback–controlled exercise versus conservative care for patellofemoral pain syndrome. Arch Phys Med Rehabil. 2001;82(12):1692–1695.
18. Akkaya N, Ardic F, Ozgen M, et al. Efficacy of electromyographic biofeedback and electrical stimulation following arthroscopic partial meniscectomy: a randomized controlled trial. Clin Rehabil. 2012;26(3):224–236.
19. Bloom R, Przekop A, Sanger TD. Prolonged electromyogram biofeedback improves upper extremity function in children with cerebral palsy. J Child Neurol. 2010;25(12):1480–1484.
20. Van K, Hides JA, Richardson CA. The use of real-time ultrasound imaging for biofeedback of lumbar multifidus muscle contraction in healthy subjects. J Orthop Sports Phys Ther. 2006;36(12):920–925.
21. Fino PC, Peterka RJ, Hullar TE, et al. Assessment and rehabilitation of central sensory impairments for balance in mTBI using auditory biofeedback: a randomized clinical trial. BMC Neurol. 2017;17(1):41.
22. Booth AT, Buizer AI, Harlaar J, et al. Immediate effects of immersive biofeedback on gait in children with cerebral palsy. Arch Phys Med Rehabil. 2019;100(4):598–605.
23. Bortone I, Leonardis D, Mastronicola N, et al. Wearable haptics and immersive virtual reality rehabilitation training in children with neuromotor impairments. IEEE Trans Rehabil Eng. 2018;26(7):1469–1478.
24. Calabrò RS, Naro A, Russo M, et al. The role of virtual reality in improving motor performance as revealed by EEG: a randomized clinical trial. J Neuroeng Rehabil. 2017;14(1):53.
25. Bell KM, Onyeukwu C, McClincy MP, et al. Verification of a portable motion tracking system for remote management of physical rehabilitation of the knee. Sensors (Basel). 2019;19(5):1021.
26. Maggio MG, De Cola MC, Latella D, et al. What about the role of virtual reality in Parkinson disease's cognitive rehabilitation? Preliminary findings from a randomized clinical trial. J Geriatr Psychiatry Neurol. 2018;31(6):312–318.
27. Duffell LD, Paddison S, Alahmary AF, et al. The effects of FES cycling combined with virtual reality racing biofeedback on voluntary function after incomplete SCI: a pilot study. J Neuroeng Rehabil. 2019;16(1):149.
28. Van De Ridder JM, Stokking KM, McGaghie WC, et al. What is feedback in clinical education? Med Educ. 2008;42(2):189–197.
29. Jie LJ, Kleynen M, Meijer K, et al. The effects of implicit and explicit motor learning in gait rehabilitation of people after stroke: protocol for a randomized controlled trial. JMIR Res Protoc. 2018;7(5):e142.
30. Kleynen M, Braun SM, Rasquin SM, et al. Multidisciplinary views on applying explicit and implicit motor learning in practice: an international survey. PLoS One. 2015;10(8):e0135522.
31. Schwartz MS, Andrasik F, Editor. Biofeedback A practitioner's guide. New York City: The Guilford Press; 2016.
32. Wolpert DM, Miall RC, Kawato M. Internal models in the cerebellum. Trends Cogn Sci. 1998;2(9):338–347.
33. Wolpert DM, Diedrichsen J, Flanagan JR. Principles of sensorimotor learning. Nat Rev Neurosci. 2011;12(12):739–751.
34. Giggins OM, Persson UM, Caulfield B. Biofeedback in rehabilitation. J Neuroeng Rehabil. 2013;10:60.
35. Wolf SL. Electromyographic biofeedback applications to stroke patients. A critical review. Phys Ther. 1983;63(8):1448–1459.
36. Basmajian JV. Clinical use of biofeedback in rehabilitation. Psychosomatics. 1982;23:67–73.•• **The article reviewed the recent**

promising techniques for task-oriented biofeedback within the field of neurorehabilitation.
37. Huang H, Wolf SL, He J. Recent developments in biofeedback for neuromotor rehabilitation. J Neuroeng Rehabil. 2006;3:11.
38. Stanton R, Ada L, Dean CM, et al. Biofeedback improves performance in lower limb activities more than usual therapy in people following stroke: a systematic review. J Physiother. 2017;63(1):11–16.
39. Moreland J, Thomson MA. Efficacy of electromyographic biofeedback compared with conventional physical therapy for upper extremity function in patients following stroke: a research overview and meta-analysis. Phys Ther. 1994;74:534–543.
40. Schleenbaker RE, Mainous AG. Electromyographic biofeedback for neuromuscular reeducation in the hemiplegic stroke patient: a meta-analysis. Arch Phys Med Rehabil. 1993;74(12):1301–1304.
41. Diekfuss JA, Grooms DR, Bonnette S, et al. Real-time biofeedback integrated into neuromuscular training reduces high-risk knee biomechanics and increases functional brain connectivity: a preliminary longitudinal investigation. Psychophysiology. 2020;57(5):e13545.
42. Yucha C, Gilbert C. Evidence-based practice in biofeedback and neurofeedback. 2004. Association of Applied Psychophysiology and Biofeedback (http://www.aapb.org).
43. Pichiorri F, Mattia D. Brain-computer interfaces in neurologic rehabilitation practice. Handb Clin Neurol. 2020;168:101–116.
44. Patel K, Sutherland H, Henshaw J, et al. Effects of neurofeedback in the management of chronic pain: a systematic review and meta-analysis of clinical trials. Eur J Pain. 2020;24:1440–1457.
45. Morone G, Pisotta I, Pichiorri F, et al. Proof of principle of a brain-computer interface approach to support poststroke arm rehabilitation in hospitalized patients: design, acceptability, and usability. Arch Phys Med Rehabil. 2015;96:S71–8.
46. Marzbani H, Marateb HR, Mansourian M. Neurofeedback: a comprehensive review on system design, methodology and clinical applications. Basic Clin Neurosci. 2016;7(2):143–158.
47. Sitaram R, Ros T, Stoeckel L, et al. Closed-loop brain training: the science of neurofeedback. Nat Rev Neurosci. 2017 Feb;18 (2):86–100. Epub 2016 Dec 22. Erratum in: Nat Rev Neurosci. 20(5):314(2019).
48. Alhasan H, Hood V, Mainwaring F. The effect of visual biofeedback on balance in elderly population: a systematic review. Clin Interv Aging. 2017;12:487–497.
49. Barcala L, Grecco LA, Colella F, et al. Visual biofeedback balance training using wii fit after stroke: a randomized controlled trial. J Phys Ther Sci. 2013;25(8):1027–1032.
50. Laver KE, George S, Thomas S, et al. Virtual reality for stroke rehabilitation. Cochrane Database Syst Re. 2015;2015(2):CD008349.
51. Hung JW, Chou CX, Hsieh YW, et al. Randomized comparison trial of balance training by using exergaming and conventional weight-shift therapy in patients with chronic stroke. Arch Phys Med Rehabil. 2014;95(9):1629–1637.
52. Morone G, Tramontano M, Iosa M, et al. The efficacy of balance training with video game-based therapy in subacute stroke patients: a randomized controlled trial. Biomed Res Int. 2014:580861.
53. Ghanbari Ghoshchi S, De Angelis S, Morone G, et al. Return to work and quality of life after stroke in Italy: a study on the efficacy of technologically assisted neurorehabilitation. Int J Environ Res Public Health. 2020;17:5233
54. Kuo YL, Wang PS, Ko PY, et al. Immediate effects of real-time postural bio-feedback on spinal posture, muscle activity, and perceived pain severity in adults with neck pain. Gait Posture. 2019;67:187–193.
55. Piggott L, Wagner S, Ziat M. Haptic neurorehabilitation and virtual reality for upper limb paralysis: a review. Crit Rev Biomed Eng. 2016;44(1–2):1–32.
56. Tramontano M, Morone G, De Angelis S, et al. Sensor-based technology for upper limb rehabilitation in patients with multiple sclerosis: a randomized controlled trial. Restor Neurol Neurosci. 2020;38(4):333–341.
57. Friston K. What is optimal about motor control? Neuron. 2011;72 (3):488–498.
58. Brown H, Friston KJ, Bestmann S. Active inference, attention, and motor preparation. Front Psychol. 2011;2:218.
59. Fitzgerald TH, Dolan RJ, Friston K. Dopamine, reward learning, and active inference. Front Comput Neurosci. 2015;9:136.
60. Wilke MA, Hartmann C, Schimpf F, et al. The Interaction Between Feedback Type and Learning in Routine Grasping With Myoelectric Prostheses. IEEE Trans Haptics. 2020;13:645–654.
61. Bell JD, Macuga KL. Goal-directed aiming under restricted viewing conditions with confirmatory sensory feedback. Hum Mov Sci. 2019;67:102515.
62. Tamburella F, Moreno JC, Valenzuela DSH, et al. influences of the biofeedback content on robotic post-stroke gait rehabilitation: electromyographic vs joint torque biofeedback. J Neuroeng Rehabil. 2019;16(1):95.
63. Makino H, Hwang EJ, Hedrick NG, et al. Circuit mechanisms of sensorimotor learning. Neuron. 2016;92(4):705–721.
64. Yip SL, Ng GY. Biofeedback supplementation to physiotherapy exercise programme for rehabilitation of patellofemoral pain syndrome: a randomized controlled pilot study. Clin rehabil. 2006;20 (12):1050–1057.
65. Abd El Rhman Ahmed A, Sayed Shoukry KE, El Maksoud GMA, et al. Influence of biofeedback and task oriented training on hand skills in children with spastic cerebral palsy. J Med Sci. 2019;19:63–68.
66. MacIntosh A, Desailly E, Vignais N, et al. A biofeedback-enhanced therapeutic exercise video game intervention for young people with cerebral palsy: a randomized single-case experimental design feasibility study. PLoS One. 2020;15(6):e0234767.