Expert Review of Medical Devices

ISSN: 1743-4440 (Print) 1745-2422 (Online) Journal homepage: https://www.tandfonline.com/loi/ierd20

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To cite this article: Giovanni Morone, Grazia Fernanda Spitoni, Daniela de Bartolo, Sheida Ghanbari Ghooshchy, Fulvia Di Iulio, Stefano Paolucci, Pierluigi Zoccolotti & Marco Iosa (2019): Rehabilitative devices for a top-down approach, Expert Review of Medical Devices, DOI: 10.1080/17434440.2019.1574567

To link to this article: https://doi.org/10.1080/17434440.2019.1574567

Accepted author version posted online: 24 Jan 2019.

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Publisher: Taylor & Francis

Journal: *Expert Review of Medical Devices*

DOI: 10.1080/17434440.2019.1574567

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Morone Giovanni[1,2], **Spitoni Grazia Fernanda**[3,4], **Daniela de Bartolo**[2,3], **Ghanbari Ghooshchy Sheida**[2,3], **Di Iulio Fulvia**[4], **Paolucci Stefano**[1,2], **Zoccolotti Pierluigi**[3], **Iosa Marco**[2]

1 Private Inpatient Unit, Santa Lucia foundation IRCCS, Rome, Italy.
2 Clinical Laboratory of Experimental Neurorehabilitation, Santa Lucia Foundation IRCCS, Rome, Italy.
3 Department of Psychology, Sapienza University of Rome;
4 Laboratory of Neuropsychology, IRCCS Santa Lucia Foundation, Rome, Italy.
4 UOC 3 Neurorihabilitation Santa Lucia Foundation IRCCS, Rome, Italy.

Corresponding author

Morone G, MD; Ph.D

ORCID: 0000-0003-3602-419

Private Inpatient Unit, Santa Lucia foundation IRCCS, Rome, Italy.
Clinical Laboratory of Experimental Neurorehabilitation, Santa Lucia Foundation IRCCS, Rome, Italy.
Tel 0651501006
Fax 0651501004
g.morone@hsantalucia.it

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Giovanni Morone[1,2,*], **Grazia Fernanda Spitoni**[3,4], **Daniela de Bartolo**[2,3], **Sheida Ghanbari Ghooshchy**[2,3], **Fulvia Di Iulio**[4], **Stefano Paolucci**[1,2], **Pierluigi Zoccolotti**[3], **Marco Iosa**[2]

1 Private Inpatient Unit, Santa Lucia foundation IRCCS, Rome, Italy.
2 Clinical Laboratory of Experimental Neurorehabilitation, Santa Lucia Foundation IRCCS, Rome, Italy.

3 Department of Psychology, Sapienza University of Rome, Rome, Italy
4 Laboratory of Neuropsychology, IRCCS Santa Lucia Foundation, Rome, Italy.
4 UOC 3 Neurorihabilitation Santa Lucia Foundation IRCCS, Rome, Italy.

***Corresponding author:**

Giovanni Morone

ORCID: 0000-0003-3602-419

Private Inpatient Unit, Santa Lucia foundation IRCCS, Rome, Italy.

Clinical Laboratory of Experimental Neurorehabilitation, Santa Lucia Foundation IRCCS, Rome, Italy.

Tel 0651501006

Fax 0651501004

g.morone@hsantalucia.it

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ABSTRACT

Introduction: In recent years, neurorehabilitation has moved from a “bottom-up” to a “top down” approach. This change has also involved the technological devices developed for motor and cognitive rehabilitation. It implies that during a task or during therapeutic exercises, new “top-down” approaches are being used to stimulate the brain in a more direct way to elicit plasticity-mediated motor re-learning. This is opposed to “Bottom up” approaches, which act at the physical level and attempt to bring about changes at the level of the central neural system.

Areas covered: In the present unsystematic review, we present the most promising innovative technological devices that can effectively support rehabilitation based on a top-down approach, according to the most recent neuroscientific and neurocognitive findings. In particular, we explore if and how the use of new technological devices comprising serious exergames, virtual reality, robots, brain computer interfaces, rhythmic music and biofeedback devices might provide a top-down based approach.

Expert commentary: Motor and cognitive systems are strongly harnessed in humans and thus cannot be separated in neurorehabilitation. Recently developed technologies in motor-cognitive rehabilitation might have a greater positive effect than conventional therapies.

Keywords: top-down approach, neurorehabilitation, technological devices, cognitive-motor rehabilitation, bottom-up approach.

1 Introduction: The top-down approach to neurorehabilitation

Traditional rehabilitation is based on bottom-up approaches that act on the distal physical level (bottom) and are aimed at influencing the neural system (top) in order to rehabilitate patients by exploiting residual neural plasticity mechanisms [1]. An increasing number of studies are pursuing a different, top-down approach that exerts more direct action on the central nervous system to recover peripheral functions. The idea that the cognitive sphere should also be more involved in motor rehabilitation is not new. Indeed, the "Perfetti" rehabilitative method, which was developed by Professor Carlo Perfetti in the 1950s for patients with stroke sequelae, considered it fundamental to involve the cognitive processes concerned with movement and movement behavior in rehabilitation [2]. The top-down approach is a more general theoretical approach that primarily opposes the notion that patients should be passive during rehabilitation. [1]. According to this approach and to the growing body of literature concerned with it during the last two decades, an important number of technological devices have been created with the intention of increasing the effectiveness of rehabilitation by adopting a top-down approach. In this regard, multiple feedback systems (i.e. exergame, serious game) as well as complex biofeedback systems (i.e. EMG, IMUs for muscle contraction or movement and posture analysis) have been used to increase subjects' cognitive involvement. Also in accordance with the top-down approach, robots and electromechanical devices that were initially developed for the intensive repetition of the same movement during arm or gait rehabilitation have recently been re-designed to include different technological solutions for increasing cognitive processing during motor rehabilitation. This paper is an unsystematic expert review of the rehabilitation devices developed in accordance with the top-down approach. This review also discusses the controversy between top-down and bottom-up approaches with respect to the technologies adopted. Table 1 presents the schema of

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this review based on the most recent and promising devices developed in accordance with a top-down approach. These devices can be divided according to the technologies used or to the sensorial channel adopted to provide feedback information to patients. Because some of them use more than one channel, we have categorized them according to the technologies adopted [3]: serious exergames, virtual reality, robots, brain computer interfaces, with the exception of acoustic devices that are often specifically developed to use only acoustic cues. This clusterization is often more theoretical than practical. A clear example (detailed below) is the integration of serious exergames in robotic devices. Another important issue is that these rehabilitative devices are often inspired by rehabilitation principles; therefore, even though they are often defined as rehabilitative devices, they are often technological environments or supports that are helpful for developing rehabilitation tasks. In fact, it is important not to consider a device as rehabilitative per se, but as useful for the rehabilitative principles it applies. This approach is subsequent to the one promoted by our group in previous studies in which we changed the question of whether a “rehabilitative device” is effective into for whom it is effective [4].

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2 From Serious Exergames to Virtual Reality

The initial evidence about the efficacy of videogames in improving cognitive functions came from the literature on healthy subjects which showed that videogame players outperform non-videogame players in visuo-attentional tasks [5], such as visual search [6] or visual inhibition [7]. Broadly speaking, it seems that, with respect to non-players, videogame players are able to enlarge their attentional buffer and to allocate more executive resources and attention to cognitive tasks. Moreover, a growing body of evidence suggests that videogames might also enhance other cognitive skills not strictly related to visuo-spatial abilities. For example, authors who investigated the effect of videogames on the speed of set-shifting agreed that videogame players showed a smaller task switching cost and that this effect seemed due to the better capacity of these players to control their attentional resources [8,9]. Moving to an issue closer to our topic, action videogame players also exhibit similar behavior. In everyday language, when we refer to an "action video game" we are referring to a video game that emphasizes physical challenges, including hand–eye coordination and reaction time. In the action game, the player typically controls the avatar (the protagonist). The avatar must navigate (walk or run), collect objects and avoid obstacles (https://en.wikipedia.org/wiki/Action_game). A recent meta-analysis of the impact of action video games on perceptual, attention and cognitive skills indicated that these video games robustly enhance the domains of top-down attention and executive cognition [10]. From a top-down perspective, it seems reasonable to infer that just as computer game devices enhance the attentional buffer and executive control, this improvement might affect the motor system in different ways. This hypothesis has been supported in recent studies which showed that action videogames are also effective in motor learning and motor recovery. Figure 1 shows the flow of information from the device to the subject and from the subject to the device. Usually in devices adopted for cognitive rehabilitation the rehabilitative principles are contained in the visual, acoustic and cognitive information provided to the subject, whereas minimal movements are required for the subject to interact with the device. Conversely, in the devices developed for motor rehabilitation the rehabilitative principles define the movements the subject must use to interact with the virtual world. For example, most of the devices developed to improve walking ability require that the patient take real steps, e.g., on a treadmill, to move the avatar in the video game. Conversely, in devices aimed at improving navigation ability, an aspect that is more related to superior cognitive functions (i.e., spatial memory, landmark recognition, exploration, etc.), importance is given mainly to the information provided by the virtual environment, wheareas minimal movements of a joystick or only verbal responses are required of the patient [11].

From the literature we have learned that motor therapies based on computer game interfaces are effective in several motor functions such as balance [12-13], posture and sensory information [14] and range of motion [14] and arm rehabilitation [15, 16, 17]. Among these devices, one good

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example is the Riablo device, which allows for a wide rehabilitation spectrum including a combination of rehabilitative principles such as biofeedback with the inertial motion sensors and the exergame [18,19].

Months of rehabilitation may be necessary before a patient can regain full or even partial recovery. For this reason, the constant repetition of specific exercises is crucial in physical rehabilitation. Unfortunately, repetition may cause tedium and a decline in alertness, which results in the patient performing the exercise incorrectly. In videogame therapy, this seems to be managed by the constant alternation of the sensory stimuli provided by the consoles.

As recently reviewed by Föcker et al. [20], the neuroplastic modifications observed during action videogames primarily took place in areas covering the fronto-parietal networks of attention and executive functions. For example, Bavelier and colleagues [21] used brain imaging to test the hypothesis that action videogames may cause changes in the mechanisms that supervise attention allocation and executive control. For this purpose, they compared attentional network recruitment and distractor processing in action gamers versus non-gamers as attentional demands increased. They found that moving distractors elicited smaller activation of the visual motion-sensitive area (MT/MST) in gamers as compared to non-gamers, suggesting an early filtering of irrelevant information by gamers. As expected, in non-gamers they found larger recruitment of a fronto-parietal network as the attentional demands increased. In contrast, gamers scarcely engaged this network as attentional demands increased. The interpretation of the authors was that the reduced activity in the fronto-parietal network (which is hypothesized to control the allocation of top-down attention) matched well with the hypothesis that players might allocate attentional resources more automatically, permitting a better initial filtering of irrelevant information. Similar results were obtained with an Event Related Potentials paradigm of an attentional visual field task [7]. The authors found increased amplitudes in the later visual ERPs, which are thought to index top–down enhancement of spatial selective attention via increased inhibition of distractors. Finally, several studies showed that videogames affect the dorsal striatum [22, 23], the right posterior parietal

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cortex [24], entorhinal cortex, hippocampus, occipital cortex [25], right hippocampal formation, and right dorsolateral prefrontal cortex, as well as both hemispheres of the cerebellum [23].

It is important to note, as recently highlighted in a review by Tieri and colleagues (2018), that video-game based applications differ from virtual reality (VR) in many regards, including degree of immersivity and interaction, as well as the sensory-motor interaction between the user and the virtual environment [26]. As virtual reality is more immersive and interactive, it might be even more effective than serious exergames in increasing cognitive involvement in motor rehabilitation sessions. BTS-Nirvana, for example, is a semi-immersive therapy system for motor-cognitive rehabilitation in neurological conditions. It employs virtual scenarios with which the patient has to interact guided by the therapist, thus increasing rehabilitative determinants [27-28] linked to executive, attentive and visuospatial skills during motor training. [29,30]

Virtual Reality can be based on the use of the head-mounted display, a wearable device consisting of two small displays mounted close to the eyes and a head-tracking system that updates the left and right images according to the observer's head movements; the audio is delivered via earphones. Most recent head-mounted displays are furnished with external sensors able to track the hand movements in real time, thus allowing for a good level of interaction with the virtual environment. Examples include Oculus Rift Oculus VR USA [31] or HTC Vive, Valve Corporation, USA [32]. Powerwall screen is an alternative, less immersive, possibility for VR, combined with glasses for 3D vision and an optical or ultrasonic tracking system [33]. Finally, the Cave Automatic Virtual Environment (CAVE) consists of a square room usually created by four or six back projected screens joined together that, combined with the dedicated glasses for 3D vision, provide a continuous projection surface and head-tracking device that allows displaying real-time images from the participant's point of view, while the audio stimuli are typically delivered by a set of speakers positioned around the CAVE [34, 35, 26].

Gamito and colleagues (2017) used virtual reality based serious game intervention as an innovative implementation rehabilitation method in patients with stroke sequelae. The results

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were promising in that they showed improved memory and improved performance on attention tasks consisting of daily life activities [36]. In another investigation, the adjunction of cognitive rehabilitation to treadmill walking training was more effective than the treadmill alone in reducing the risk of falling in Parkinson's disease, as demonstrated by Mirelman et al. (2016). The authors aimed to investigate both motor (treadmill) and cognitive (virtual reality) functions in order to define this approach as integrated [37]. Piron and colleagues demonstrated that virtual reality based feedback could enhance upper limb function in cardiovascular survivors [38]. Yates et al. [39] studied various virtual reality gaming systems for rehabilitating the upper extremities of post-stroke patients. VR-based rehabilitation simulates real-life activities by asking patients to work on self-care skills in a setting that is difficult to create in a hospital environment. More important, certain "motor requests" are shaped only in the everyday-life enviroment. In VR exercises, patients face situations that commonly occur in daily activities; for example, an exercise might require the patient to move 8 objects (i.e., glass objects) in a virtual dining room with a bell ringing in case of errors. The basic idea of the top-down approach is to involve higher cognitive functions also in motor exercises. In fact, several executive functions are activated in these motor exercises.

- planning: in order to see all the target objects, the performer needs to plan a systematic exploration of the room
- working memory: the performer needs to keep in mind the number of objects already moved and to continue the exercise until the 8th item is reached
- inhibition and mental flexibility: in case of errors, the performer should inhibit the ongoing action and replace it with an appropriate one
- initiation and monitoring of action: the performer should be able to independently decide when to start and to monitor the precision of his actions

In the above-mentioned model, executive functions allow the patient to constantly repeat movements with the upper and lower limbs and to monitor balance and gait.

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Thus, VR can increase the patient's active participation, which facilitates a positive rehabilitation outcome [36].

The literature confirms that the application of virtual reality gaming rehab therapy is effective in improving body structure/function, activity level outcomes and cognitive functions in subjects affected by stroke [39, 40].

3 From acoustic cues to music therapy

The fact that rehabilitation has often been carried out in noisy gyms has led to the more common use of visual feedback without audio systems and the poor diffusion of devices with only acoustic feedback. However, visual feedback is sometimes associated with acoustic feedback [1] to provide important reinforcements. Furthermore, in some specific environments devices that include audio systems are used for top-down rehabilitation. They can be divided into two main categories of rehabilitation devices: devices that provide simple acoustic cues and devices to use for music therapy.

The devices that provide acoustic cues can be subdivided into those that provide external cues or those that provide a biofeedback of the subject's performance. A simple example of the former is the use of a metronome to encourage symmetry in the walking steps of patients with Parkinson's Disease [41, 42]. Temporally predictable Rhythmic Auditory Stimulation (RAS) has been shown to have an immediate beneficial effect on gait by increasing speed, stride length and improving symmetry and stability [43, 44]. Due to their problems with the internal generation of rhythmic patterns related to basal ganglia deficits, Parkinson's disease patients are good candidates for RAS as well as for music therapy. The basal ganglia (BG) are part of extensive cortical-subcortical circuits involved in a variety of motor and non-motor cognitive functions associated with the cortico-striato-thalamo-cortical circuitry involved in temporal processing, encoding, decoding and evaluation of temporal relations or temporal structure [45]. This is the mechanism

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underpinning the possible motor benefits for patients with Parkinson's Disease shown after RAS and musicotherapy, such as training based on the tango [46].

For stroke patients, gait training was developed using the walk-even feedback device [47]. Results of this study indicated that in chronic stroke survivors the combination of strength and gait training with real-time feedback might reduce temporal asymmetry and enhance weight-bearing on the affected side.

More recently new devices have been developed to provide a sonification of movements more in accordance with music-therapy principles [48]. The basic idea is that of Luria [49] according to which pre-motor areas of the brain are responsible for the conversion of individual motor impulses into consecutive kinetic melodies, which are at the basis of functional harmonious movements. Sonification of arm movements have been tested in patients with stroke using inertial sensors [50] (for a review on wearable inertial devices see [51]) and the PhysioSonic tracking system. In this study, the acoustic feedback allows for improved proprioception and body awareness in patients with motor impairment [52].

Among these technologies, a new innovative rehabilitative one integrates auditory cues and visual feedback in order to improve locomotion in patients with motor impairment. An example of this is the Biodex Gait Trainer 3 [53], which allows directly addressing patients' step length, step speed and right-to-left time distribution (step symmetry).

Movement sonification technologies, as well as music therapy, seem to be promising and further research should be conducted on new devices that are being developed now and on those that will be developed in the coming years.

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4 Robots and electromechanical devices: from bottom-up to top-down approaches

In the last decade, Robotic devices (i.e., Armeo Spring® and Armeo Power®, Mit Manus®, Nerebot®, Lokomat Pro®) [4,54,55] have been widely used in rehabilitation hospitals. Many devices were developed to perform a bottom-up exercise as a mere repetition of movement, with little attention given to the cognitive processes that regulate motor functions. Recently, we have witnessed the integration of cognitive stimuli with motor stimuli through feedback systems, biofeedback, VR and exergame. There are, however, many possibilities for improving and personalizing neurorehabilitation therapy. The man-machine interface of robots should be improved in the future to provide greater clarity about what is being measured and assessed, as indicated in Iosa and colleagues' [56] three laws of neurorobotics. In this scenario, the combination of different systems of conditioning and recovery of the motor gesture, such as biofeedback and exergame with robotic devices, seems very promising. Robotic devices could include videogame-based or virtual reality-based augmented feedback during training exercises. As it is possible to adapt the exergame level, the scenario of the exergame gives patients the right adaptation following cognitive impairment and also makes it possible to increase the challenge of the exercise, which is different from the use of robots alone. Thus, during exercise the Bottom Up motor rehabilitation component (motor intensity and task-oriented) and the Top Down (attention, visuo-spatial ability) motor cognitive rehabilitation component are integrated with robots.

Some devices that use acoustic stimulation as complementary cues have been proposed in upper [57] and lower limb robotic rehabilitation [58]. This approach is not only useful for patients with Parkinson's Disease, but has been suggested also for other neurological patients, such as those with stroke. The acoustically-paced treadmill has been proposed for walking training after stroke [59]. This device allows setting gait and is coupled best with the beat of metronome rates near the preferred cadence [60].

The most recent versions of Lokomat as well as a robotic application developed by the PERCRO Laboratory in Pisa include the combination of VR with robotic exoskeleton for lower and upper limb rehabilitation, respectively [61-63]. Furthermore, a recent article by Calabrò and coworkers indicated that the use of 2D virtual reality coupled with the Lokomat Pro allows for more evident activation of the premotor, precuneus and associative visual areas as compared to Lokomat Pro

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training without virtual reality. As affirmed by the authors, the activation of particular areas, like the premotor-parieto-occipital desynchronization of γ-oscillations, is a marker of activation of sensorimotor and visuo-spatial associative areas concerning motor planning and selective muscle activation also in robotic training [64].

5 Brain connected devices

Neurofeedback and Brain Computer Interfaces are two promising approaches for providing a biofeedback of central nervous system activities to the patient (and to the therapist). NIRS, fMRI and EEG could be used as devices providing biofeedback. Although Neurofeedback is emerging as a promising technique that enables self-regulation of ongoing brain oscillations with empirical evidence attesting to its clinical benefits, a solid theoretical basis is still lacking on the manner in which Neurofeedback is able to achieve these outcomes [65]. A recent study interlinked evidence from experimental findings that encompass a broad range of intrinsic brain phenomena involved in neurofeedback. It is important to highlight that although some brain mechanisms are related to the central nervous system, they can be defined as “bottom-up” (i.e., the mechanisms of neural synchronization), whereas others can be defined as “top-down”, such as the regulation of internal brain states [66]. Dynamic systems plus control-theoretical principles and activity-dependent homeostatic forms of brain plasticity are complex factors that should be controlled to avoid an approach in which the brain is treated like a black box a signal can be extracted from that has no clear physiological meaning [66])

Several authors have recently explored the potential of brain-computer interfaces (BCIs) for functional recovery after stroke [67, 68]. The BCI technology is based on volitional modulation of electroencephalographic (EEG) sensorimotor rhythms (SMRs).

The use of BCI has been promoted to enhance motor recovery in accordance with the top-down approach in combination with robotic training [69, 70] and functional electrical stimulation [71]. In a recent study, a BCI-controlled robotic mirror therapy system was proposed for lower limb recovery following stroke. An experimental paradigm that includes four states was introduced to

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combine robotic training (bottom-up) and mirror therapy (top-down) approaches. A BCI system was presented to classify the electroencephalography (EEG) evidence [72]. Despite promising results, most of these devices are prototypes.

A prototype that is now commonly used in clinical settings is the Promoter. This is a BCI system that uses real-time estimation and classification of SMRs state modulation to drive an instant BCI visual feedback (ie, a cursor motion on a screen) and the corresponding "virtual hand" action displayed on a wide monitor covering the real affected hand of the patient. When the patient is able to imagine the closure of his/her affected hand, the virtual hand is closed, providing realistic visual feedback to the patient [67, 73].

6. Expert Commentary

Based on the aforementioned studies, the following question arises: How do attention and executive control enhance the effect of the video game-based/augmented feedback/top down based therapy for motor recovery? All studies on the Top-Down approach to rehabilitation support the idea that it increases patients' participation in their own rehabilitation and greater participation has been highlighted as a positive prognostic factor for a good rehabilitation outcome [74]. Nevertheless, the question still remains about how participation can increase the outcome of motor rehabilitation.

The most convincing hypothesis is that the improvement of executive and attentional functions might affect the accuracy of Goal Directed Movements (GDMs). In physical and rehabilitation therapy, GDMs are defined as voluntary movements that are organized around behavioral goals, environmental context and task specificity, as distinguished from reflexive passive movements [5]. GDMs are initiated entirely from within the CNS; their performance improves with practice and they can recruit further actions such as reflexes and /or rhythmic movements.

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With reference to Attention, and considering its multicomponential nature, it is possible to argue that two of its components, Arousal (i.e., physiological activation level) and Alertness (i.e., state of high sensitivity to incoming stimuli) could have an important role in GDMs.

Furthermore, several authors have agreed about the multidimensional structure of executive control and have proposed to label as "executive" the higher order cognitive functions such as planning, working memory, inhibition, mental flexibility, and the initiation and monitoring of action. All of these functions are alternately involved during motor rehabilitation with computerized devices. Virtual Reality exercise seems to best describe the involvement of executive functions in motor rehabilitation [75].

To briefly sum up the above, improving voluntary movements should be considered an essential aim of motor rehabilitation; in top down motor rehabilitation, action videogames might enhance attention and executive functions, which in turn lead to improvement of the GDMs. A clear example is the passive mobilization of lower limbs provided by the first robots developed for gait recovery. The goal of walking is to move the body from one position to another, but most of these robots performed "walking in place". The addition of a virtual scenario with a walking avatar may have enhanced the efficacy of locomotor rehabilitation by restoring to walking its fundamental nature of goal-directed movement.

However, given the wide range of devices and possible feedback, i.e., including virtual environments and serious exergames (briefly summed up in Figure 2), it is difficult to provide evidence-based conclusions about the efficacy of the top-down approach administered to patients using technological devices. However, we can point out some limits of this approach by changing the question about their efficacy into for whom they can be effective. Despite promising results using devices in a top-down approach, it is important to define who might benefit from top-down rehabilitation. Patients with severe cognitive impairment, for example, might find more difficulties than facilitations using a top-down device. This point was highlighted by Mehrholz et al. [76]: the correct use of new technologies must rely on the information regarding the types of patients and the

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phase of rehabilitation that will benefit from specific technologies. For example, patients who have greater voluntary motor function in the affected limb can perform intensive training also with conventional therapy [77,78] and may prefer less constrained, more ecological and more variable exercises performed in a real environment than mediated by some technological devices [4]. Physical condition is not the only factor that determines the best class of neurorobot users: the patient's psychological profile can also be important in attaining superior motor outcomes with robot training compared to conventional therapy [79]. Bragoni et al. [80] identified the level of anxiety of patients as a negative prognostic factor for robotic therapy but not for conventional therapy. By contrast, patients who saw themselves as the chief causal factor in managing their recovery showed greater probability of a better outcome with technological rehabilitation. This kind of fear could be due to the notion that technologies are not trustworthy because they lack human feelings, expertise, and common sense, or because they seem ludic, without real clinical usefulness [81]. However, the wide diffusion of technological interfaces (computers, smartphones, tablets, artificial intelligence also in automotive and other fields, etc.) will probably contribute to a greater acceptance of technologies in rehabilitation.

It should be noted that some controversial results have been reported about a top-down / cognitive approach to motor rehabilitation independently of the devices used, questioning this approach on the basis of interesting findings related to the bottom-up mechanisms at the origin of human movements [82]. A recent Cochrane review also reported that explicit motor learning seemed equally effective as implicit motor learning post stroke [83]. As reported in that review, at the moment it is impossible to draw reliable conclusions regarding a higher effect of top-down / cognitive / explicit motor learning with respect to bottom-up / purely motor / implicit motor learning. High quality studies with large samples are needed to test top-down versus bottom-up approaches in clinically relevant contexts.

7. Five-year view

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The rehabilitation that is evolving through the massive use of technological devices that can help therapists carry out more complex and multimodal training with assist-as-needed strategies faces one crucial challenge. The development of technological devices is moving towards the application of the top-down approach. This approach seems to be effective because it encourages the recovery of addictive plasticity by increasing the cognitive contents that are functional for a specific motor action we wish to train, taking into consideration factors such as the motor and cognitive level of the patient, fatigue, frustration, intra- and inter-session mood and motivation. In particular, greater participation may be related to rehabilitation based on more ecological goal-directed movements, even though it is often administered using virtual environments.

However, we still need to define what a top-down approach really means. Exergame using a monitor and a computer to provide a multitude of feedback could be based on many different interfaces: joysticks, mouse pads, inertial measurement units, and sensors that acquire specific neural signals that might be monitored/trained during rehabilitation such as electromyography, electroencephalography, fNIRS signal, etc. On the other hand, even the voice of the therapist giving commands and feedback to the patient during conventional manual therapy could be considered a top-down reinforcement. For all of these reasons, in the next few years we must better define the neurophysiological principles of the top-down approach and their bioengineering applications. It is important to train physiotherapists to become more focused on an integrated motor-cognitive therapy in order to overcome the differences among rehabilitation techniques. Modern therapists should have specific training with regard to cognitive motor neurophysiology and neuropsychology and with technological devices that provide opportunities for increasing cognitive load during motor therapy by performing an exercise using a top down approach.

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Key issues

- Novel Top-down approaches have been used as a brain stimulant and as one of the new rehab methods for implementing new therapies in cognitive and motor rehabilitation. Nevertheless, there is still a need for more research in the area of top-down rehabilitation to elicit more assistive approaches in motor and cognitive therapy driven by neural plasticity in order to enhance the efficacy of therapies with cost effective programs in a shorter period of time.

- Devices with exergame and virtual reality interaction are able to provide more attention and executive resources for cognitive tasks (i.e. visuo-spatial abilities).
- As an effective method, Rhythmic Auditory Stimulation (RAS) has been shown to have an immediate beneficial effect on gait in Parkinson's disease patients by improving symmetry and stability.
- All cognitive motor-based rehabilitation devices aim to enhance motor learning and neural reorganization by boosting attention and executive functions related to goal-directed movements; however, the relationship between motor and cognitive areas has not yet been completely understood.
- The combination of both recent top-down and classical bottom-up techniques might have an additional positive effect beyond conventional rehabilitation treatment.
- In the future, physiotherapists and psychologists should increase the exchange of patient-related information regarding top-down cognitive motor physiotherapy.

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Funding

This paper was not funded.

Declaration of interest

The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript. This includes employment, consultancies, honoraria, stock ownership or options, expert testimony, grants or patents received or pending, or royalties.

Reviewer disclosures

Peer reviewers on this manuscript have no relevant financial or other relationships to disclose.

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Figure Legends

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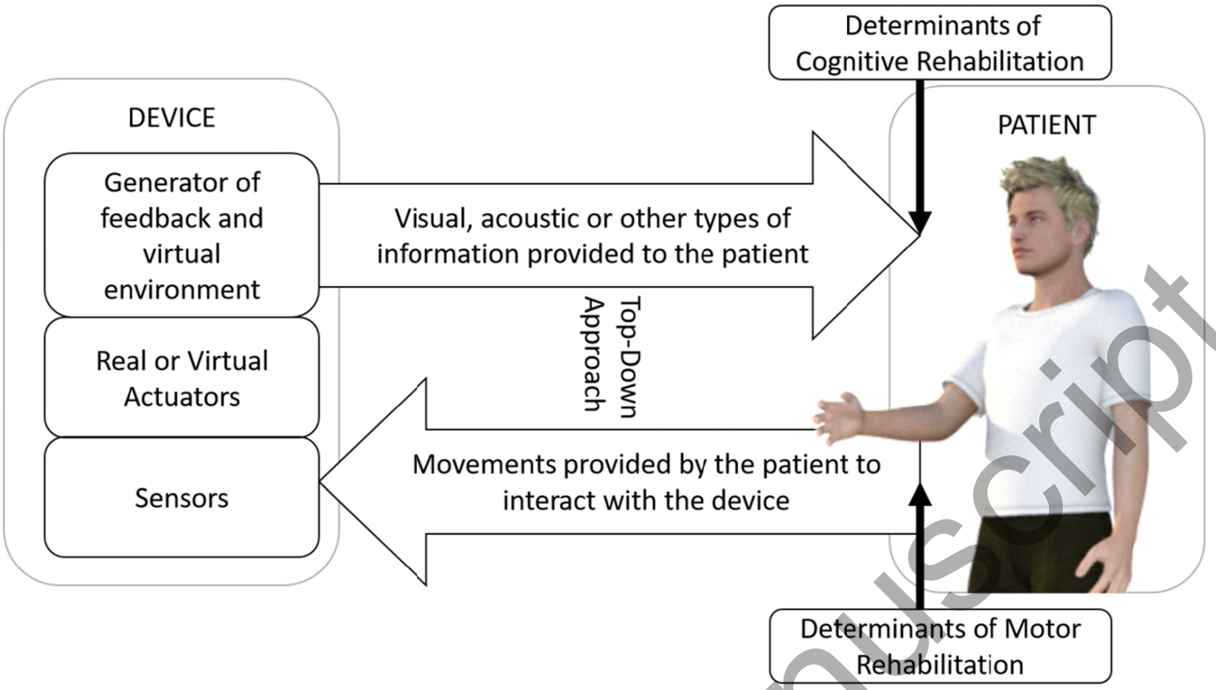

Figure 1. Schema of Technological Top Down Approach in motor-cognitive rehabilitation.

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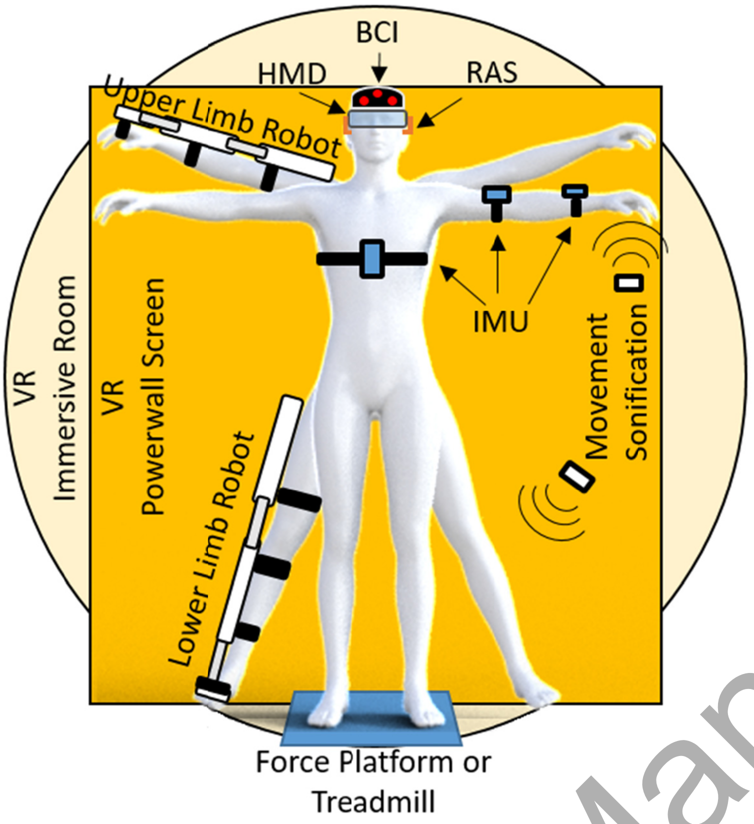

Figure 2. Schema of technological devices used for a Top Down rehabilitation: Virtual Reality (VR) can be generated in an immersive room, using a powerwall screen, or a Head Mounted Display (HMD). The VR and serious exergame can be used in combination with a force (or pressure) platform for the recovery of balance, with a treadmill for the walking recovery or with Inertial Measurment Units (IMUs). Upper and lower limb robots can be used to assist the movements of the patient. Auditory stimuli can mainly be administered using external Rhythmic Auditory Stimulation (RAS) or by sonification of the movements of the subject. The brain signals could also be used by means of a Brain Computer Interface (BCI).

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Tab. 1: most recent and promising devices developed in accordance with a top-down approach

Device category	**Subdivision**	**References reported in this review**	**Example of devices**
Virtual Reality	Head-Mounted Display	Hoffman et al., 2014 Niehorster et al., 2017	Oculus RIFT, HTC vive,
	Powerwall screen	Ortner et al., 2012	VisWall-LCD™
	Immersive room	Brennan et al., 2013	VisCube™ M4 CAVE Immersive 3D Display
	Virtual Reality for Rehabilitation	De Luca R. et al., 2018 Maggio MG et al., 2018	BTS-Nirvana
Serious exergame	Using platforms for balance	Pirini et al., 2018 Jakob et al.,2018	Khymeia VRRS Tymo Tyromotion
	Using joysticks for arm rehabilitation	Jakob et al.,2018 Turolla et al., 2013 Fusco et al., 2018	Pablo Tyromotion VRRS Reha-slide
	Using IMUs	Lupo et al. 2018	Riablo
Audio systems	Acoustic external cues	Thaut et al., 2018 Lee et al., 2018	Rhythmic Auditory Stimulation
	Acoustic feedback	Krishnan et al., 2016	Walk-Even
	Movement sonification	Vogt et al., 2010 Raglio et al., 2013	PhysioSonic Sonichand
	Music-therapy	http://www.biodex.com/physical-medicine/products/gait-trainer/music-assisted-therapy	Biodex Gait Trainer 3.
Robots and mechatronic devices	Plus visual top-down approach	Ricklin et al., 2018 Frisoli et al., 2009	Lokomat with serious exergame, Percro Lab Robot
	Plus acoustic top-down approach	Roerdink et al., 2007	Acoustically paced treadmill
	Plus virtual reality	Mirelman et al., 2016	Training with treadmill in VR
Brain connected devices	Neurofeedback	Renton et al., 2017	NeurOptimal®
	Brain Computer Interfaces	Picchiorri et al., 2015 Morone et al., 2015	Mental imagery BCI assisted

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