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TOPICAL REVIEW

Emergence of flexible technology in developing advanced systems for post-stroke rehabilitation: a comprehensive review

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Keywords: stroke, assistive and rehabilitation systems, flexible/stretchable electronics, e-textile, soft robotics, biosignals acquisition, functional electrical stimulation

Abstract

Objective. Stroke is one of the most common neural disorders, which causes physical disabilities and motor impairments among its survivors. Several technologies have been developed for providing stroke rehabilitation and to assist the survivors in performing their daily life activities. Currently, the use of flexible technology (FT) for stroke rehabilitation systems is on a rise that allows the development of more compact and lightweight wearable systems, which stroke survivors can easily use for long-term activities. *Approach.* For stroke applications, FT mainly includes the 'flexible/stretchable electronics', 'e-textile (electronic textile)' and 'soft robotics'. Thus, a thorough literature review has been performed to report the practical implementation of FT for post-stroke application. *Main results.* In this review, the highlights of the advancement of FT in stroke rehabilitation systems are dealt with. Such systems mainly involve the 'biosignal acquisition unit', 'rehabilitation devices' and 'assistive systems'. In terms of biosignals acquisition, electroencephalography and electromyography are comprehensively described. For rehabilitation/assistive systems, the application of functional electrical stimulation and robotics units (exoskeleton, orthosis, etc) have been explained. *Significance.* This is the first review article that compiles the different studies regarding FT based post-stroke systems. Furthermore, the technological advantages, limitations, and possible future implications are also discussed to help improve and advance the flexible systems for the betterment of the stroke community.

1. Introduction

Stroke is a neurological disorder in which the brain is unable to receive an adequate amount of oxygen due to obstruction in blood flow to the brain cells. It is a life-changing event that can affect the subject's cognitive and emotional state as much as their physical functions. Studies show that individuals recovering from a stroke often experience helplessness, frustration, and social isolation, which is linked to increased depression and decreased ability to manage their daily activities [1, 2]. According to a study conducted in 2015, there are about 25.7 million stroke survivors worldwide [3]. One recent study indicates that there are approximately 116.4 million DALYs (disability-adjusted life-years) and 5.5 million deaths due to stroke [4].

Mainly there are five post-stroke phases that comprise hyper-acute (0–24 h), acute (1–7 days), early subacute (7 days to 3 months), late sub-acute (3–6 months), and chronic (>6 months) [5, 6]. Among the stroke survivors, around 50% suffer from upper limb paresis, i.e. weakness or inability to move the upper limb [7]. Thus, the primary aim of post-stroke care is to assist the patients in their everyday life activities and rehabilitate them for effective recovery of lost functions. This allows them to regain their independence and reintegrate into the social community. Currently, the most common stroke rehabilitation methods for restoring motor functions are occupational and physical therapies [8]. In these approaches, task-specific and repetitive training is performed to induce motor recovery based on motor learning and neuroplasticity mechanisms.

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Motor rehabilitation is supposed to support the brain in reorganizing its neural networks and relearning the skills that were lost due to stroke conditions [9, 10].

With the advancement in science and technology, new stroke rehabilitation methods have been introduced, which include the use of functional electrical stimulation (FES) and robotics assistance system [11]. FES is used as a non-invasive rehabilitation tool to restore the motor skills of stroke survivors by stimulating the targeted nerves via applying electrical impulses through the skin surface, thus, inducing movements in paretic muscles [12–14]. This method was first implemented on hemiplegia patients by Moe *et al* [15], which was later improved by Kralj *et al* [15] to treat subjects with neural disorders. Several studies confirm the efficacy of FES in recovering different muscle movements, for instance, restoring hand grasp [16–18], walking [19, 20], arm reaching [21, 22], standing [23, 24], and upper-limb rehabilitation [25–27]. On the other hand, the main objective of robotics-based rehabilitation systems in stroke therapy is to provide assistance in restoring impaired limb movements. These systems mainly include orthoses, exoskeletons, and other robotics units that allow the rehabilitation of upper and lower limbs, depending on the stroke severity [28–39]. An additional advantage of robotics systems includes the ability to measure the dynamic and kinematic parameters of the subject's motion during the therapy. This allows monitoring the subject's performance while performing the rehabilitation exercises by estimating their speed, range of motion, task execution accuracy, etc [40].

The ultimate objective of rehabilitation therapies is to restore the brain connections for motor recovery and thereby function. Therefore, along with the therapist's assistance, the subject's active participation can improve the outcomes. In this regard, the use of motor imagery (MI) paradigm of the brain-computer interface (BCI) system seems to be an innovative approach to neurorehabilitation [41–44]. MI training consists of the representation of imaginary movements of limbs without physically performing it. This ability of the brain to imagine a movement is used for restoring motor skills. MI activates some of the neural circuits that are also involved in the real movements, and thus, could induce functional redistribution of neuronal circuits [45, 46]. An MI-BCI is a computer-based system that records the electroencephalography (EEG) signals and translates the user's intention to perform the specific task based on MI events, for example, activating the muscle stimulator or controlling a robotic rehabilitation unit. Such MI-BCI systems have widely been used in stroke rehabilitation for motor and functional recovery [47–66]. Apart from MI [67], steady-state visual evoked potential (SSVEP), another BCI paradigm, has also been used for controlling assistive devices by the use of subject's EEG activities. SSVEP is produced in response to external visual stimulus and can be generated by alternating graphical patterns, flashing lights, and flickering images. Usually, their frequencies lie in the range of low (1–3.5 Hz) to high (75–100 Hz) frequency bands, and based on the frequency range, the SSVEP-BCI system executes a required action [68]. Such systems have been largely used for wheelchair applications in which the different directions of the wheelchair are maneuvered by a set of pre-defined frequency values [69–72].

In addition to EEG, the use of surface electromyography (EMG) has also been proven as an efficient approach to control rehabilitation and assistive devices. The use of EMG as feedback allows to analyze the real-time muscle activity and provides information regarding the amount of rehabilitation required [39]. For instance, in the case of FES device, the EMG module will record the muscle potential and provide feedback to the FES block for adjusting the electrical stimulation according to the requirement [73–75]. Also, EMG is used for controlling assistive devices, which comprises of controlling electric wheelchairs [76, 77] and robotic orthoses/exoskeletons [78–80].

The above-mentioned biosignals acquisition and rehabilitation approaches are delivering promising results; however, the current systems/devices are bulky, rigid, and need special expertise to operate them. Hence, there is a need to improve them by transforming these conventional systems into 'Smart Systems' that would be wearable, flexible, compact, lightweight, portable, and user-friendly (depending on their mode of application). Recent advances in flexible technology (FT) have offered a variety of innovative solutions to the given challenges. In neurorehabilitation applications, the term '*Flexible Technology*' mainly includes the development of: (a) Flexible/stretchable electronics based bio-sensing systems/electrodes, (b) e-textile (electronic textile) based systems, and (c) Soft robotics-based flexible prototype, e.g. flexible exoskeleton/orthosis. Flexible electronics (FE) is an advanced technology that enables the fabrication and incorporation of sensors and electronic circuits on flexible, bendable, stretchable, and twistable substrates [81]. The concept of FE was introduced in the 1960s when Crabb and Treble developed the first flexible solar cells [82]. From 1990 to 2000, flexible transistors and transducers have been designed primarily by using flexible organic thin films [83–85]. Later, as the field of FE advanced, its range of biomedical applications increased, including artificial electronic skin (e-skin) [86–89], vital sign monitoring [90–92], and neural interfaces [93]. Another FT is the 'e-textile' application in which the electronics is embedded into the stretchable garments/-textile to perform actuating and sensing functions [94, 95]. In healthcare, e-textile advantages are significant and have widely been adopted in monitoring physiological parameters [96–98], biosignals acquisition [99, 100], gait and postural assessment

[101, 102], and prosthesis control [103]. Additionally, soft robotics is in high demand nowadays due to newly added features, including the high degree of freedom (DOF) and range of motion along with attained flexibility and portability, which has never been achieved with rigid-link robotics [104]. Therefore, soft robots have contributed to the various platforms; for instance, used in performing manipulation tasks (e.g. grasping) [105, 106], mobility assistance (walking) [107], and other medical applications [108–110]. The application of FT in stroke rehabilitation and assistive systems will be described comprehensively in later sections of this manuscript.

To date, numerous review articles have been published related to the healthcare applications of FT, which comprises flexible textile electrodes for biosignals monitoring [99], wearable electronics and smart textiles [111], e-textiles in neurorehabilitation [112], wearable sensors and systems with application in rehabilitation [113], and FE for soft robotics [114, 115]. However, none of them focuses on providing a detailed overview of different flexible methodologies for developing flexible stroke rehabilitation and assistive systems. Hence, this review article has compiled the implementation of several FTs for stroke application (FE, e-textile and soft robotics) and has comprehensively described them in terms of the development of biosignal acquisition unit and rehabilitation/assistive systems. Moreover, current limitations and future research directions are also discussed for possible improvements of flexible stroke rehabilitation systems.

2. Searching criteria

Before the systematic search, inclusion criteria (IC) and exclusion criteria were defined. Only papers that met all the IC listed below were selected:

IC1: The article must be written in English.

IC2: The publication date should be on or after the year 2010.

IC3: The study should be based on FT in terms of flexible electronics OR e-textiles OR soft robotics.

IC4: The study must report information about any of the following: signal acquisition approaches used for stroke systems (EEG and EMG) OR stroke rehabilitation systems (either conventional or BCI based) OR assistive systems (exoskeleton, orthosis, or other robotic units).

IC5: Among the soft robotics systems, only those studies are included that have validated their rehabilitation effect on stroke users.

EC1: The papers that involve FT but do not address its application for stroke systems.

EC2: The papers that contain the development of stroke systems without the use of FT.

To perform the systematic review, we searched for articles in PubMed, ScienceDirect, IEEE, and Scopus databases using the keywords: FE, stroke rehabilitation, BCI, brain computer interface, brain-machine interface, brain machine interface, neural-machine interface, neural machine interface, biosignal acquisition systems, e-textile, soft robotics, neurorehabilitation devices, FES, robotics systems, and assistive stroke systems. Figure 1 illustrates the overall screening process for inclusion and exclusion of the research articles. Initially, 1565 papers were found, and among them, 237 duplicates were removed (level 1). According to the IC, the remaining 1328 papers were assessed and based on their titles and abstract, 645 articles were excluded (level 2). This resulted in a total of 657 manuscripts for full-text screening, out of which only 26 research articles fulfilled the IC and are included in this review article (level 3).

3. FT in post-stroke systems

Post-stroke systems consist mainly of two building blocks: (a) biosignal acquisition systems to collect physiological signals like EEG and EMG, and (b) assistive and rehabilitation devices that are used to perform/assist in rehabilitation exercises (for instance, electrical stimulation devices and robotics exoskeleton). The use of bioelectronics, sensing technology, bioinstrumentation, telecommunication, and signal analysis techniques have played a vital role in developing the aforementioned systems. In the past, the system/device compactness and its transformation into wearable form was always a big question, restricting the adoption of such systems for long-term neural applications. However, the recent advancement in FT has allowed the development of flexible, stretchable, and compact systems that entail the features of signal acquisition, microcontroller operations, sensing capability, and wireless transmission [113]. The overall schematic of FT applications in stroke rehabilitation systems has been shown in figure 2.

3.1. Biosignal acquisition systems and electrodes

3.1.1. Brain signals acquisition systems/electrodes

Based on the process of recording brain activities, the brain acquisition techniques are of three types, i.e. invasive, semi-invasive, and non-invasive [116]. The invasive method is also called ‘Intracortical Acquisition Scheme’ in which the electrodes are implanted

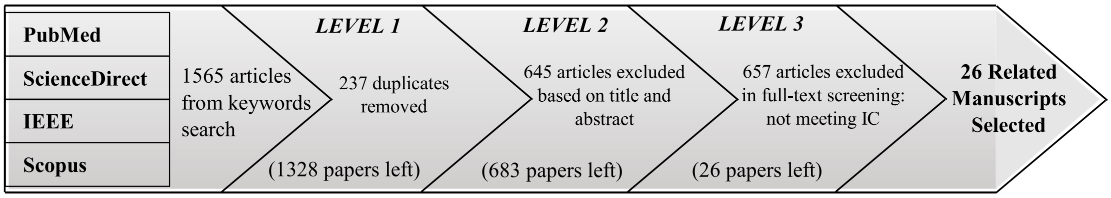

Figure 1. Literature search process and results.

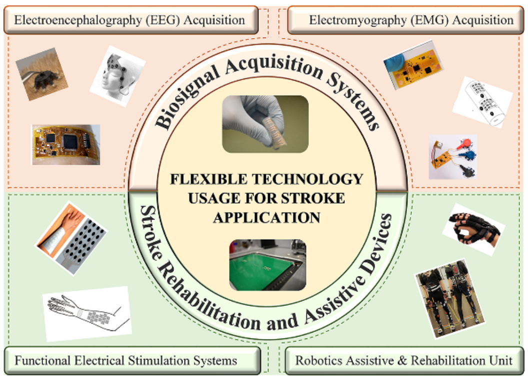

Figure 2. Overview of FT application for stroke rehabilitation systems.

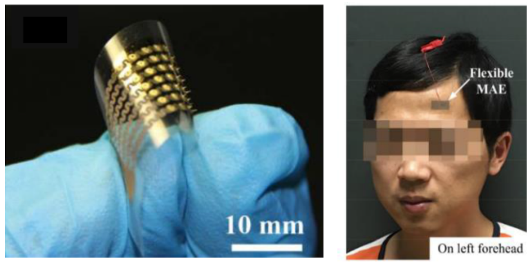

Figure 3. Flexible MAE. Reproduced from [136]. CC BY 4.0.

into the brain's cortex to record the action potential generated by neurons firing [117]. Secondly, semi-invasive techniques are mostly used to record signals from the brain's cortical surface using electrocorticogram (ECoG) [118, 119]. Lastly, the non-invasive technique, which does not require electrode implantation and records the signals from the brain scalp via EEG. EEG possesses high temporal resolution; however, it depicts a much lower spatial resolution and is more sensitive to external noises as compared to invasive and semi-invasive methods [120]. Non-invasive BCI systems are preferred for acquiring brain signals due to their comfort, feasibility, safety, portability, and low cost. Additionally, according to studies [121, 122], subjects prefer non-invasive systems for their medical diagnosis and treatment despite having low-quality signals. Therefore, the non-invasive EEG systems are the most commonly used in BCI-assisted stroke rehabilitation systems that are based on either gel [123–125] or dry electrodes [126, 127]. However, the current EEG systems [128–131] are heavy, bulky, and contain rigid hardware components, hence, not suitable for long-term mobile EEG monitoring on a daily basis. Thus, to fill this gap and to make EEG recording comfortable and feasible for day-to-day use, FE has stepped into the field of developing 'Flexible EEG Systems/ Electrodes'.

In recent research, Mahmood *et al* have developed a flexible, portable, and wireless EEG acquisition device (termed as 'SKINTRONICS') for BCI-assisted neurorehabilitation system [132]. The overall system includes an FE-based circuit, three flexible elastomeric electrodes for the scalp, and a skin electrode. It presents a remarkable reduction of electromagnetic and noise interference compared to standard EEG systems [131, 133–135]. The device works on the SSVEP-BCI paradigm and has been tested on six human subjects for real-time controlling of a wireless wheelchair, slide changing of presentation software, and wireless mini-vehicle. The obtained results show higher control accuracy of $94.01 \pm 3.6\%$ and $96.24 \pm 3.4\%$ at intervals of 0.512 s and 1.024 s, respectively. In another research, a flexible microneedle array electrode (MAE) has been developed by Ren *et al* [136], which is ideal for biosignal monitoring, including the wearable EEG measurement. For electrode fabrication, the flexible polyethylene terephthalate substrate has been used. On the substrate, the conductive patterns and microneedle array are deposited by laser-direct writing and magneto-rheological drawing lithography techniques, respectively (figure 3). The MAE are tested for eyes blink, close and open features and their performance is compared with the standard Ag/AgCl electrode and flexible dry electrode (FDE). The result shows that the EEG monitoring ability of MAE is similar to that of Ag/AgCl electrodes, which proves the feasibility and possible usage of flexible MAE for biosignal measurement. Also, flexible dry EEG electrodes have been developed by Grozea *et al* [137] that are made of flexible metal coated polymer bristles (figures 4(a)–(c)). The experimental results show that the FDEs are able to record alpha rhythms, P300 event-related potentials, MI BCI paradigms and auditory evoked potential. Moreover,

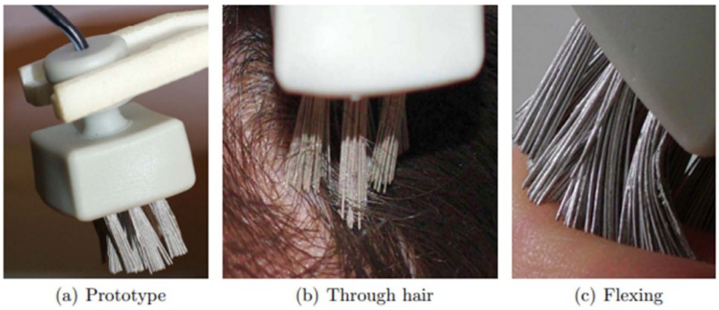

Figure 4. Silver-coated polymer bristles prototype: (a) prototype (b) through hair (c) flexing. Reproduced from [137]. © IOP Publishing Ltd. All rights reserved.

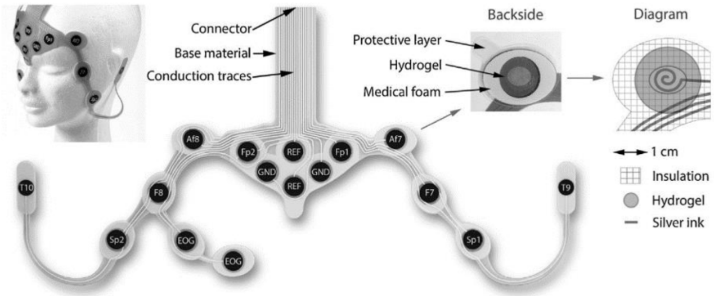

Figure 5. BrainStatus consisting of ten electroencephalography (EEG) electrodes, two electrooculography (EOG) electrodes, two ground electrodes and two reference electrodes. Reprinted from [138], Copyright (2014), with permission from Elsevier.

it is also found that the quality of EEG signals acquired from flexible electrodes are closer to the signals that are recorded using standard gel-based electrodes (within the range of 7–44 Hz). Lepola *et al* [138] developed a flexible screen-printed EEG electrode set called 'BrainStatus' (figure 5), consisting of 16 hydrogel-coated electrodes (ten EEG recording electrodes, two electrooculography electrodes, two ground electrodes, and two reference electrodes). BrainStatus has been tested on two clinical patients, and the quality of the acquired EEG signal was excellent and comparable to the conventional EEG electrodes. Hence, this system can be feasible and able to provide effective solution for long-term EEG monitoring of subjects with stroke or other neural disorders.

Apart from conventional EEG recording systems in which the electrodes are placed on the scalp, Norton *et al* introduced a new flexible EEG system. The system is capable of providing long-term (>14 days) EEG recordings with the electrodes positioned at the auricle (outer ear surface) and the adjacent regions (mastoid area) [139] (figure 6). This dry electrode system consisted of a collection of gold electrodes with 300 nm thickness and coated with a spray-on-bandage material that ensures reliable recordings during normal daily activities. Finally, the device has been tested on a group of volunteers using an SSVEP-BCI text-speller and achieved an average accuracy of 93% with a spelling rate of 2.3–2.5 letters per minute, two to three times slower than a conventional cap EEG system on the hairy scalp.

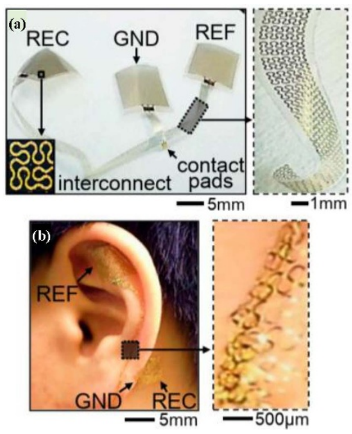

Figure 6. (a) Epidermal electronics, composed of three electrodes (REC, GND, and REF)), with magnified view of the latter (Right). (b) Device laminated on the auricle and mastoid (Left) and the magnified interconnect (Right). Reproduced from [139]. CC BY 4.0.

Moreover, nowadays, the application of e-textiles technology in a biopotential acquisition is growing gradually, which allows the development of flexible and stretchable textile-based EEG monitoring electrodes [99]. However, the main limitation of applying textile electrodes in EEG recording is hair on the scalp. Therefore, e-textile electrodes are placed on non-hairy regions, for instance, on the forehead and behind the ears [140]. Matiko *et al* [141] have developed and tested a self-powered EEG headband containing integrated flexible solar panels and screen-printed conductive electrodes. The device was tested on 12 subjects, and different emotion responses were identified via EEG classification. The system performance was compared with the commercially available passive electrodes, and the obtained outcome showed a correlation result of 70.88%. Recently, La *et al* [142] have also developed screen-printed e-textile patches, which have been tested for EEG assessment against eye-opening and closing activities, with an electrode placed behind the ear in the mastoid region. The results were quite promising and showed that the e-textile electrode contained smaller motion artifacts than commercial rigid sensors.

3.1.2. EMG acquisition systems/electrodes

There are two main types of EMG measurements; intramuscular EMG and surface EMG (sEMG) [143]. Intramuscular EMG is an invasive method that is used to study the deep muscles [144, 145]. It is a time-consuming process and requires special clinical expertise to insert the electrodes deep into the muscles; hence, rarely been used in practical applications [146]. On the other hand, sEMG is a non-invasive technique that acquires EMG signals from large surface areas and has widely been used for recording the electrical potential of superficial muscles [147]. sEMG has a low-signal resolution, possesses a relatively narrow frequency band (20–500 Hz), and is highly susceptible to movement artifacts as compared to invasive EMG [148–150]. However, the sEMG signal quality can be improved by selecting the appropriate electrode location [147], and optimum electrode size [151]. Despite having inherent limitations, sEMG is practically preferred because of its non-invasiveness [152].

As the sEMG based research for neurorehabilitation applications advances, the need of flexible and stretchable EMG electrodes arises to provide novel and advance solutions for monitoring muscle activities. The flexible EMG electrodes are more feasible than conventional electrodes, as they can be easily placed on curved body surfaces and are also comfortable for long-term myosignal recordings. Additionally, they can be embedded into wearable devices of different shapes and can minimize the overall compactness of the system [153]. In [154], flexible sEMG electrodes are used to control FES activation, which plays a vital role in delivering stroke rehabilitation. The system is tested on eight healthy subjects by positioning the flexible EMG electrodes on extensor carpi radialis, extensor digitorum communis, and extensor carpi ulnaris muscles of the forearm (figure 7). The FES is adjusted based on the muscle activities and provides sufficient stimulation for wrist extension, hand opening, and ulnar deviation. In another related research [155], on-skin technology has been used to develop a flexible, stretchable, and power efficient sEMG electrode grid for controlling FES stimulation (figure 8). Xu *et al* [156] developed a flexible skin-mounted sensing platform that can monitor sEMG via sensing, ground, and reference electrodes (figure 9(a)). The designed sEMG sensing platform is fabricated as a flexible electronic skin tattoo containing thin gold and polyimide layers. The electronic tattoo is attached to the biceps and triceps surface, and depending on the generated muscle signals, the extension and flexion of the robotic arm's elbow joint are controlled (figures 9(b) and (c)). Thus, such a flexible sEMG controlled robotic control system can be implemented to develop robotic assistive devices for stroke rehabilitation. Fall *et al* [157] developed a smart textile based sEMG electrodes, made of metal polymer-glass hollow-core fiber. The electrodes testing are performed by recording the muscle activities of biceps and forearm flexor muscles.

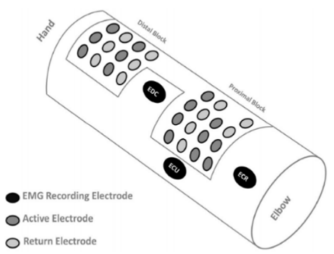

Figure 7. Multi-contact set-up visualized for the left arm: Electrode array for FES with a fixed configuration of two blocks, i.e. a proximal and a distal (close to the hand) block with 15 and 12 contacts respectively, and three flexible electrodes for EMG recording. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Journal of Neuroengineering and rehabilitation [154] Multi-contact functional electrical stimulation for hand opening: electrophysiologically driven identification of the optimal stimulation site, De Marchis *et al*, © 2016.

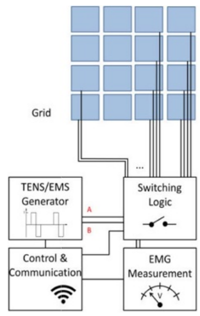

Figure 8. Components of the planned electrode grid. The EMS generator produces the stimulation signals, which are directed to different electrode configurations over the switching logic. A control and communication unit synchronizes the components. It controls the stimulation parameters and collects the measurements from the EMG unit. Reproduced with permission from [155].

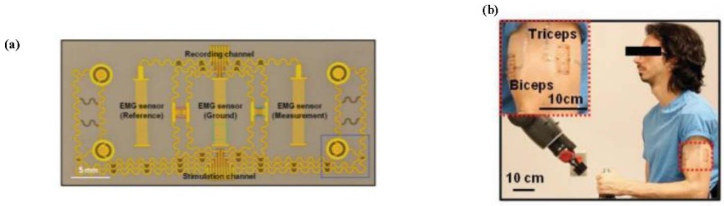

Figure 9. (a) Simple, multifunctional device with skin-like physical characteristics and capabilities in both sensing and stimulation (b) devices on the bicep and triceps (inset) during control of the angle of the elbow of a robot arm [156]. John Wiley & Sons. © 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

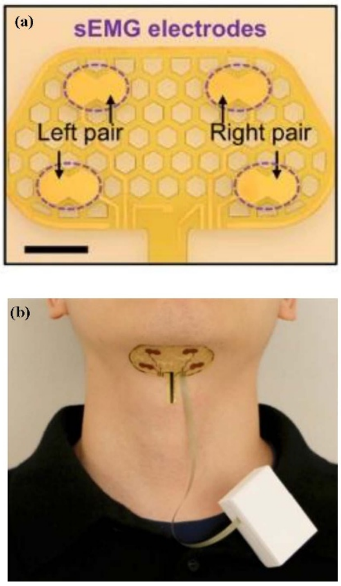

Figure 10. Basic layouts and configurations of the sensor patch system. (a) Enlarged photo of the sEMG recording electrodes. Scale bar, 1 cm. (b) Schematic illustration of the sensor patch connected with a portable unit clipped on the wearer's clothing for remote data transmission and powering. From [158]. Reprinted with permission from AAAS.

The obtained results confirm that the smart sEMG electrodes possess the performance similar to commercial gold-plated electrodes. Hence, during stroke rehabilitation, such sEMG units can be used as a biofeedback. It can provide real-time data of muscular activities and command the rehabilitative robots to provide assistance based on the muscle requirement. Moreover, in [158], a skin-mountable flexible sensor patch has been developed for the patients suffering from dysphagia (difficulty swallowing disorder), which is caused by different neural disorders, including the stroke [159]. The patch is designed for the submental area (under the chin) to provide the remote monitoring of muscle activity (sEMG) during the swallowing tasks (figure 10). The monitoring of swallowing events during the post-stroke rehabilitation of dysphagia is very important as it provides information regarding the level of muscular improvement and allows to adjust the rehabilitation exercises accordingly. Preliminary testing on a patient with dysphagia, and on a healthy control validates the effectiveness and feasibility of this system.

3.1.3. Overview of biosignals acquisition systems

Table 1 shows an overview of different studies in which FT has been used to develop electrodes and systems for measuring EEG and EMG signals.

3.2. Stroke rehabilitation and assistive devices

3.2.1. FES based rehabilitation

It has been shown that the upper limb stroke rehabilitation performed via the FES technique results in better performance as compared to the physical therapy alone [171–174]. For an effective implementation of FES in stroke rehabilitation, the vital parameters of stimulation (onset therapy time [172, 175] and dosage [176, 177]) should be chosen with great caution. Apart from having significant advantages, the current FES devices possess the limitation of providing 'Selective Stimulation'. For instance, when focusing on the recovery of a particular hand function, it is necessary to position the electrodes precisely over the muscle motor point to produce specific muscular contraction [178]. The motor point is an 'optimized electrode area' where the required stimulation effect is attained with minimal electrical stimulation. As current FES devices normally use a pair of large gel electrodes, several current paths are produced under the applied electrodes, stimulating different muscles. This causes the compromising of selective activation of targeted muscles and also induces muscle fatigue [179]. Hence, to overcome this shortcoming and provide selective stimulation, the flexible multiple electrodes array has been developed to easily be placed on curvy surfaces and cover multiple targeted areas on a single location [154, 155, 180–183]. It allows the selective activation of individual electrodes to deliver the selective stimulation to targeted muscles. Additionally, studies showed the spatial distribution of stimulation across multiple electrodes also delays the onset of muscle fatigue [184–186].

Yang *et al* [180] developed an e-textile based flexible 24-electrode array called 'e-sleeve' for FES rehabilitation device (figure 11). The e-sleeve has been fabricated via screen printing technique and can cover multiple muscle groups, eliminating the need for precise positioning of electrodes on the targeted

Table 1. Research studies and their outcomes for the development of biosignal acquisition systems and electrodes.

Study	Designed hardware	Fabrication technique	Comments/results obtained	Possible post-stroke rehab applications
Mahmood *et al* [132]	EEG electrodes and acquisition circuit	Aerosol jet printing [160]	System ables to detect SSVEP BCI paradigm of different frequency values.	The different BCI paradigms that includes SSVEP and motor imagery, are widely used in post-stroke rehabilitation systems [161]. For instance, motor imagery is used to control the rehabilitation devices during the rehabilitation sessions (e.g. robotic unit or FES device). It allows the active participation of brain during rehabilitaion and enhances the neural plasticity and helps in active restoration of neural networks [11]. Moreover, EEG electrodes that are able to detect the alpha rhythm and work within frequency range between 0–40 Hz can also be used in motot imagery BCI application (freq. band is 8–30 Hz) [161]. Furthermore, using SSVEP may be useful for closed-loop rehabilitation approaches that make use of repetitive movement tasks [162–164]
Ren *et al* [136]	Flexible microneedle array electrode (MAE) for EEG monitoring	Laser-direct writing [165] and magneto-rheological drawing lithography [166]	Eye blinks, close and open were distinguished. (alpha rhythm detection, 9–13 Hz)	
Grozea *et al* [137]	Flexible EEG dry electrodes	Coating thin polymer bristles with silver particle	Successfully detected alpha rhythm, motor imagery, and auditory evoked potential.	
Pasi *et al* [138]	Flexible EEG electrodes set (BrainStatus)	Screen printing [167]	Able to record brain signals within the range of 0–40 Hz.	
Norton *et al* [139]	Ear-based EEG electrode systems	Microfabrication techniques, together with processes of transfer printing	Used for SSVEP based BCI spellers and obtained average accuracy of 93%	
Matiko *et al* [141]	Flexible and stretchable textile-based EEG monitoring electrodes	Screen printing [167]	Identified different emotion response and able to detect frequency range of 0.16–49.5 Hz.	
Matiko *et al* [142]	E-textile patch for recording brain signals	Screen printing [167]	Distinguished eye closing and opening movement (alpha rhythm detection, 9–13 Hz)	
Marchis *et al* [154]	Flexible sEMG electrodes	—	Activated FES stimulation device. Provided sufficient stimulation for wrist extension, hand opening, and ulnar deviation.	These flexible sEMG electrodes can sense the patient's intention of performing the specific action (e.g. hand opening). Based on intention, it only activates the selective FES electrodes to provide the required stimulation to targeted muscles during rehabilitation.
Duente *et al* [155]	Flexible sEMG electrodes	—	Activated FES stimulation.	
Xu *et al* [156]	Skin-mounted sEMG sensing platform	Spin coating [168]	Controlled robotic arms' elbow joint movement.	Can be implemented for developing robotics assistive unit for stroke rehabilitation
Fall *et al* [157]	Smart textile based sEMG electrodes	Vapor deposition technique [169]	Monitors the muscle activities from biceps and forearm flexor muscles.	Such smart electrodes can be used in stroke rehabilitation robots to control their actions based on real-time muscle activities.
Kim *et al* [158]	Flexible submental sensor patch for sEMG measurement	Rapid prototyping methods, including photolithography [170] and laser cutting [165]	Records the sEMG signal while swallowing task. Pilot testing on a dysphagia patient confirms the feasibility of flexible sensing patch.	These sEMG measurment patches can be useful is systems for analyzing the efficacy of post-stroke swallowing rehabiliation.

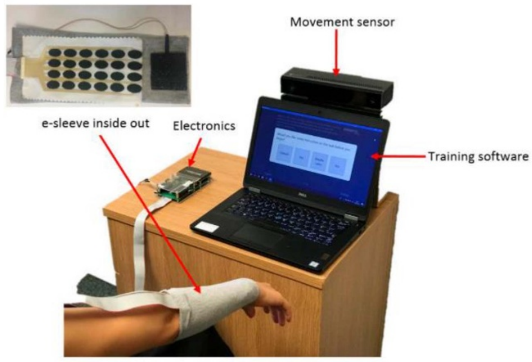

Figure 11. E-sleeve and FES training system. Reproduced from [180]. CC BY 4.0.

muscle. The developed algorithm activates the optimized combination of electrodes required to perform specific movements. The e-sleeve performance was tested on eight stroke survivors with upper limb disability by performing 'hand opening and pointing' actions. Result shows that the system selected the right combination of electrode array to achieve the targeted motion. In [154], an FE array has been used that contains 27 electrodes to deliver the FES stimulation (figure 7). The overall system comprises a kinematic glove, EMG unit, and FES module. The stimulation configuration of FES electrodes is automatically selected based on the feedback received from the kinematic glove (records finger and wrist movements) and EMG (records forearms muscles activity). The system has been tested on eight healthy subjects to perform different finger and wrist movements of left arm. Results show that the electrode array successfully provides an accurate stimulation to targeted muscles and could be feasible for stroke rehabilitation applications. Also, in [155], a flexible on-skin 80 electrode array has been developed for controlling FES stimulation with EMG feedback. At a single time, 20 electrodes can be activated via switching logic in order to provide the required stimulation to lower arm muscles for fine movement control (figure 8). For performance evaluation, the overall device containing FES and EMG measurement unit is under development phase. Yang *et al* [181] fabricated the screen-printed fabric electrode arrays (FEA), containing 24 electrodes for wearable FES device (figure 12(a)). First, optimized stimulation sites on the forearm are selected, and then FES stimulation is delivered to the targeted location via FEA. Results show the successful execution of desired movements, including 'open hand', 'pinch' and 'pointing' gestures (figure 12(b)). Hence, it can be used in stroke rehabilitation systems to provide upper limb rehabilitation therapies. Another multi-pad flexible electrode array for FES stimulation was designed by Malešević *et al* [182], which is named intelligent functional electrical stimulation (INTFES). The array is made of a flexible polyester substrate and contains 16 electrodes that can be controlled individually. The system has been tested on three stroke survivors where the electrodes are placed on forearm muscles for producing grasping movements. The selective activation of electrodes is based on flex sensors feedback that measures the muscle twitch response and automatically activates the electrodes accordingly (figure 13). The result shows that the INTFES triggers the correct electrode configuration and successfully accomplishes grasping action along with maintaining wrist stabilization. Similarly, Loitz *et al* [183] also developed multi-pad FEA for FES control in which the electrode activation is controlled by flex sensors feedback (figures 14(a) and (b)). The system has been designed specifically for stroke rehabilitation purposes and has been successfully tested on a stroke survivor to perform hand opening.

3.2.2. Robotics based rehabilitation/assistive systems

The main advantage of robotics systems over other methods in stroke rehabilitation is their possible application to subjects with extremely low or even no motor function. Many researches have shown that the robotics rehabilitation methods produce an improved stroke recovery compared to the conventional rehabilitation approaches [187]. Furthermore, the flexible design introduces flexibility that allows the subject to perform rehabilitative movements with a higher range of motion and greater ease. Despite having several advantages, robotics rehabilitation systems have limitations in terms of their massive, rigid and complex operating setup, making subjects uncomfortable and less motivated towards performing rehabilitation exercises [35, 63, 188–193]. Thus, to develop compact and flexible robotics system, the use of FT via 'Soft Robotics' comes into play. Using stretchable materials and flexible actuators, soft robotics has introduced a new paradigm for human-machine applications and has successfully been demonstrated its adaptability [194–196], agility [107, 197, 198], and sensitivity [199, 200].

Currently, the application of soft robotics in stroke robotics systems is at its rising curve and several studies have reported their implementation in assistive and rehabilitative robotics for regaining the subject's movement and motor recovery [201–203]. For post-stroke gait rehabilitation, a textile based flexible wearable robotic system has been developed [201, 202] that transmits the actuator's generated power to the paretic ankle and provides assistance during walking (figure 15). The system has been tested on nine stroke survivors (chronic phase), and results show that the paretic limb achieved an increase in ankle's swing phase dorsiflexion and improved forward propulsion. In [203], as a part of the European project 'XoSoft', a soft exoskeleton (exosuits) has been developed to assist people having mobility pathologies (figure 16). This system assists in people walking

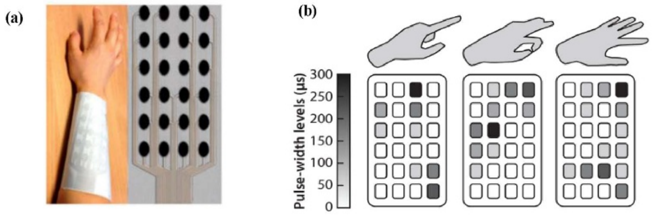

Figure 12. (a) Flexible electrode array (b) stimulation patterns for pointing, pinching and open hand gestures. Reprinted from [181], Copyright (2014), with permission from Elsevier.

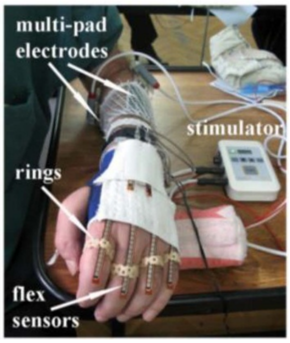

Figure 13. Sensor system for the assessment of the effects of stimulation. The flex sensors are affixed with special rings, and the glove is applied using a zipper interface. The electronics for processing are integrated into the system. The outputs are finger flexion/extension and wrist flexion/extension movements. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Journal of neuroengineering and rehabilitation [182] A multi-pad electrode based functional electrical stimulation system for restoration of grasp, Malešević *et al*, © 2012.

and provides mechanical assistance by reducing the energy requirements within a range of 10%–20%. The performance of the developed exosuit has been evaluated on stroke survivors in a straight walking scenario. It has been found that the exoskeleton provides power assistance of 9.3 ± 3.5% and 10.9 ± 2.2% for knee and hip actuation, respectively. Additionally, improvement in gait pattern and increased foot clearance has also been observed at different phases of the gait cycle. In another research, Bae *et al* [204] developed a light-weight and efficient portable soft exosuit for paretic ankle assistance during gait rehabilitation. A preliminary testing has been performed on 03 stroke patients and it demonstrates that the soft exosuit can improve paretic limb ground clearance and forward propulsion, hence, decreasing the metabolic cost of walking. Awad *et al* [205] presented a soft robotic exosuit (figure 17) and evaluate its effects on the long and short distance walking ability of stroke patients. The soft rehabilitation exosuit has been tested on six stroke patients who are in the chronic phase of post-stroke recovery. The findings report that a portable soft exosuit facilitates the farther walking distances and faster walking speeds among the stroke individuals. For post-stroke hand rehabilitation, Stilli *et al* [206] designed a novel light-weight inflatable soft exoskeleton device, called the AirExGlove. It delivers adaptive, high-dosage and gradual rehabilitation to the stroke patients affected by clenched fist deformity. Preliminary testing of AirExGlove on clenched-fist stroke patient validates a higher level of ergonomics of the soft exoskeleton in comparison with conventional robotic systems. Another soft robotic glove for upper limb rehabilitation has been developed by Yap *et al* [207] that provides grasping assistance via promoting finger flexion (figure 18). Pilot testing has been performed on two stroke patients that confirms the improvement in patient's grasping action. Recently, Cheng *et al* [208] investigates the clinical application of BCI based soft robotic glove (BCI-SRG). The randomized controlled feasibility study is performed on 11 chronic stroke patients and it is found that BCI-SRG group depicts the trends of prolonged improvements in rehabilitation scores.'

3.2.3. Overview of stroke rehabilitation and assistive devices

Table 2 shows an overview of different studies in which FT has been used to develop FES rehabilitation devices and soft robotics-based rehabilitation/assistive systems.

4. Discussion

The word 'Flexible Technology' itself is a much diversified term and possesses a wide variety of medical applications. Currently, FT is quickly emerging in research activities to provide novel healthcare solutions for the stroke community (figure 19). FT mainly includes the implementation of FE, E-textile, and Soft Robotics to develop the systems for post-stroke use. These systems are regarded as rehabilitation and assistive systems, which fall under the two broad categories. The first one is entirely operated via allocated hardware units, whereas the second one is controlled via voluntary intention of users (by using their EEG or EMG signals). Thus, exhaustive research is underway for developing biosignal acquisition electrodes/systems, assistive devices, and rehabilitation systems via flexible technology. FT is currently in its early stages of development; however, preliminary

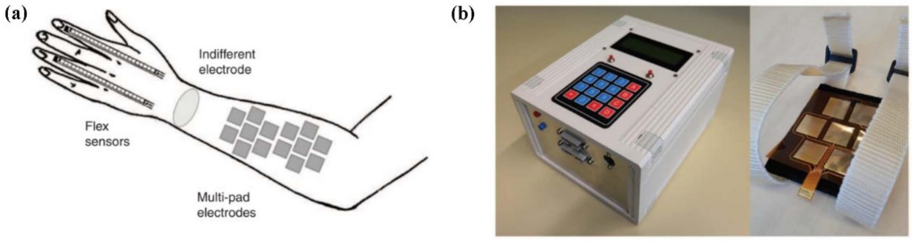

Figure 14. (a) Schematic illustration of multi-pad electrode FES with sensor feedback. (b) Left: multi-pad control hardware with front panel to connect electrodes and sensors. Right: custom-made multi-pad electrode and sleeve. Reproduced with permission from [183].

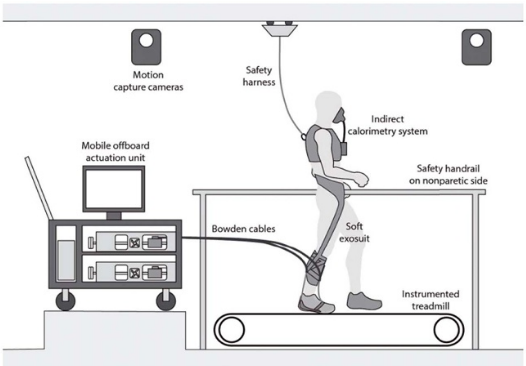

Figure 15. Illustration of experimental setup. Instrumented treadmill with the exosuit worn either powered (delivering forces generated by an off-board actuation unit) or unpowered. From [201]. Reprinted with permission from AAAS.

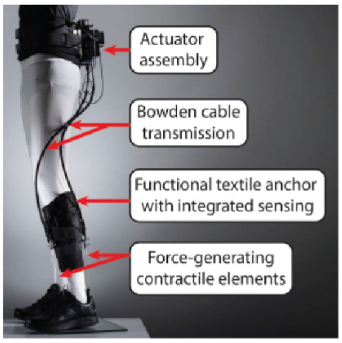

Figure 17. Overview of the soft robotic exosuit used to augment paretic ankle plantarflexion (PF) and dorsiflexion (DF) function during post-stroke hemiparetic walking. © [2020] IEEE. Reprinted, with permission, from [205].

Figure 16. Participant wearing XoSoft: (a) front and (b) back view. Reproduced with permission from [203].

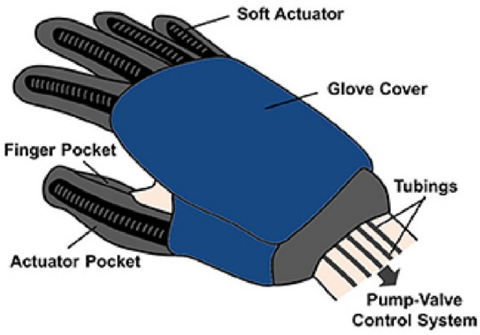

Figure 18. Overview of soft robotic glove. Reproduced from [207]. CC BY 4.0.

results are quite promising and provide the path for future innovation. In addition to the detailed explanation of FT's stroke application, we believe that some key questions need to be addressed for concluding the discussion. These queries can provide an overview regarding the advantages, limitations, and further interpretation of FT in stroke systems.

4.1. What are the key advantages of FT in post-stroke systems?

The key advantages of FT in developing medical systems for stroke patients vary based on their application mode and are comprehensively described below.

Table 2. Research studies and their outcomes for the development of stroke rehabilitation and assistive devices.

Study	Designed Hardware	Post-Stroke Rehab Applications	Comments/Results Obtained
Yang *et al* [180]	'e-sleeve' (flexible 24-electrode array) (Fabricated by Screen printing [167])	Tested on eight stroke patients for applying FES stimulation to perform upper limb rehabilitation.	System perfectly activated the optimized electrodes for carrying out 'hand opening and pointing' gestures.
De Marchis *et al* [154]	Flexible 27 electrode array	Pilot testing is performed on eight healthy subjects for applying FES stimulation. Hence, shows the potential for post-stroke rehabilitation.	System perfectly activated the optimized electrodes for carrying out hand wrist movements.
Duente *et al* [155]	Flexible 80 electrode array	Providing FES stimulation to lower arm for post-stroke rehabilitation.	20 electrodes can be activated at a single time. FES and EMG unit is under development for future testing.
Yang *et al* [181]	Fabric electrode arrays (FEA), containing 24 electrodes (Fabricated by Screen printing [167])	Pilot testing is performed on two healthy subjects for applying FES stimulation. Hence, shows the potential for post-stroke rehabilitation.	Successfully executed 'open hand', 'pinch', and 'pointing' gestures. FEA Performance is compared with plastic electrode array. Result showed the achievement of higher angular joint movement and greater repeatability by using FEA.
Malešević *et al* [182]	Multi-pad electrode based system—INTFES (INTelligent Functional Electrical Stimulation)	Tested on three stroke patients for delivering FES stimulation to a forearm during upper limb rehabilitation.	INTFES triggered the correct electrode configuration and successfully stimulates the muscles required for grasping.
Loitz *et al* [183]	Multi-pad electrode (Fabricated by Flexible printed circuit (FPC) technology	Tested on single stroke patient for applying FES stimulation to perform upper limb rehabilitation.	Provided stimulation to extensor digitorium muscle for accomplishing hand opening
Awad *et al* [201] and Bae *et al* [202]	Textile based flexible wearable robotic unit	Tested on nine stroke patients for gait rehabilitation	Increase in ankle's swing phase dorsiflexion, and improved forward propulsion has been achieved.
Natali *et al* [203]	Soft lower limb exoskeletons (exosuits)	Performance evaluation is made on one post-stroke patient for gait assistance during rehabilitation.	Improvement in gait pattern and increased foot clearance has been observed
Bae *et al* [204]	Soft robotics exosuit	Tested on 03 stroke patient for paretic ankle assistance during gait rehabilitation.	Analysis showed the improved paretic limb ground clearance and forward propulsion during walking.
Award *et al* [205]	Soft robotics exosuit	Tested on 06 chronic stroke patients for ankle assistance during gait rehabilitation.	Facilitated the farther walking distances and faster walking speeds among the stroke individuals.
Stilli *et al* [206]	Soft pneumatic exoskeleton glove (AirExGlove)	Preliminary testing of AirExGlove is performed on clenched-fist stroke patient for hand rehabilitation.	Showed higher level of ergonomics in comparison with conventional rehabilitation robots.
Yap *et al* [207]	Soft Robotic Glove	Preliminary testing of glove is performed on 02 stroke patients for hand rehabilitation.	Pilot testing confirmed the improvement in patient's grasping performance.
Cheng *et al* [208]	Brain-Computer interface based soft robotic glove (BCI-SRG)	Randomized controlled trials are performed on 11 chronic stroke patients to assess their performance in comparison with 'without BCI' soft robotic glove.	BCI-SRG group showed more improvements in rehabilitation scores as compared to SRG control group.

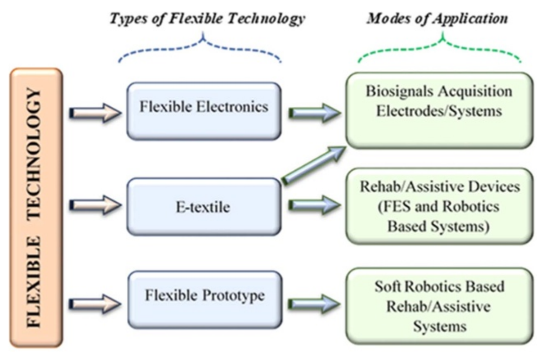

Figure 19. Overview of types of flexible technology and their modes of application.

4.1.1. FE based electrodes and systems

FE plays a vital role in developing biosignal acquisition electrodes (e.g. EEG, EMG, etc and healthcare systems (e.g. FES device, biosensors, etc). The use of FE over the traditional approaches allows the system to be more compact and portable, enabling the user to perform long-lasting rehabilitation exercises or other similar activities with a high level of comfort and ease [126]. Additionally, the FAEs eliminate the need for complex wiring, reducing the movement artifacts and recording the clean signals compared to lead-based systems. Such adhesive electrodes are also very useful for emergency medical care in ambulance work due to their 'disposability' nature. It also provides an opportunity to place the flexible module where the rigid component is challenging to place. For instance, the placement of flexible EEG sensors on the earlobe for measuring brain signals [139]. Moreover, it allows the quick and easy installation of a flexible system in case of an emergency that includes the usage of EEG headset in case of emergency for continuous monitoring of brain condition [138].

4.1.2. E-textile

The concept of e-textile (also termed as 'Smart Textile') is purely based on the concept of FT and is seen as an innovative way to revolutionize healthcare practices. The most important advantage that brings the smart textile in the high-demand list is the introduction of 'Customized Wearability'. As different electronic modules can be embedded into any clothing, a wearable system becomes more adaptable. The user can personalize its appearance depending on individual preferences and environmental changes. Furthermore, instead of using physical electronic components, some of the e-textile contain the printed modules that are printed on the stretchable textiles via conductive inks. This reduces the weight and improves its wearability, which converts the normal textile into an intelligent textile that can compute, sense, actuate and communicate (depending on the application). Within the post-stroke systems, e-textile contains a wide variety of applications, which mainly comprises fabrication of EEG electrodes [141, 142], FES stimulation electrodes [180–182], and gait rehabilitation systems [201, 202].

4.1.3. Flexible prototype for soft robotics based assistive/rehabilitation unit

In such systems, FT comes into action via 'Soft Robotics' that provides a high DOF and more flexibility while performing mobility action. Moreover, flexible exoskeletons and orthosis show promising results especially because of the reduced weight that is crucial when performing rehabilitation therapy. Two major limitations of the rigid exoskeleton that prevent it from home/community use are high cost and the requirement of expertise to operate. One of the advantages of flexible sensors and e-textile system application in soft wearable robotics is that it could potentially bring down the cost and requires less expertise to operate, which therefore makes it possible for long-term home use.

4.2. What are the limitations of FT for the development of post-stroke systems?

The limitation of FT varies depending on its mode of application.

4.2.1. FE

The primary constraint in FE-based systems/electrodes is '*Mechanical Robustness,*' i.e. the flexible components started to lose their stability and behave differently after few cycles of twisting, stretching, and bending [209]. Among flexible adhesive sensors/electrodes, the key limitation is their '*Re-usability,*' i.e. depending on the adhesion quality, the adhesive sensor needs to be replaced with a new one after few trials [210]. Another disadvantage of FE-based skin sensors is '*Unstable Output due to Motion Artifacts.*' The skin stretching causes variations in the skin potential, which can affect the sensor output and lead to generation of false readings [211]. Some people consider '*Hair Removal*' as a weakness of FE. To obtain high-quality biosignals via flexible sensors, the targeted area must be properly shaved to avoid interference caused by hair [132]. Another drawback includes the '*Difficulty of Repairing or Modifying*' the FE components in the system. Hence, great care must be taken while designing and fabricating the flexible modules.

4.2.2. E-textile

'Washability' is the main obstacle that limits the practical implementation of e-textile in healthcare. Currently, there are no standardized washing protocols available for e-textiles, and every e-textile manufacturer provides its own reliability statements for repeated washing [212]. The washing process might produce any or all of the following effects in the respective e-textile:

- *Changes in the electrical properties of the conductive path:* For instance, increase in the resistance or the loss of electrical conductivity, etc [213–215].
- *Changes in integrity:* For instance, loosening of components/wires, delamination, etc [216, 217].
- *Changes in the textile characteristics:* For instance, decreased sensing capabilities, reduced data transmission ranges, etc [218, 219].
- *Mechanical deformation:* For instance, the appearance of wrinkles in the fabrics that introduce artifacts in the sensing measurements, etc [220].
- *Functional changes:* Partial or complete functional loss of the e-textile system [221, 222].

4.2.3. Soft robotics based assistive/rehabilitation unit

Among soft robotics based rehabilitation systems, the hydraulic and pneumatic control mechanism are widely used. Such control strategies require high pressure pumps for their actuation that causes difficulties in retaining the required gripping force and therefore, result in slow actuation rates [223]. Moreover, soft robotics in rehabilitation robots often offers a lower number of DOFs as compared to classical rigid robotics systems [224]. Hence, in future design, these limitations should be taken into consideration to further increase the adaption of soft robotics in stroke rehabilitation.

4.3. Is FT used in any post-stroke system regarding the invasive and semi-invasive application?

Invasive/semi-invasive application is the best suitable ones for biosignals acquisition modules within the rehab and assistive systems. Hence, it is expected that FE-based invasive/semi-invasive biosignal acquisition systems will be developed in the future. The *in-vivo* experiments have already been performed on feline animal (cat) models to acquire their brain signals via a semi-invasive flexible ECoG sensing unit [225, 226]. The preliminary results show that flexible semi-invasive electrodes have great potential for measuring high-quality brain activities. However, it possesses several limitations, including [227]: (a) These electrodes need the surgical procedure for implantation. (b) There are chances that the body will not respond to the new external object as expected, thus, causing medical problems. (c) Complications related to the implant stability and possible neural infection can also arise. Therefore, their feasibility for human trials is still questionable, and thus, the current usage of FE in an invasive recording is restricted for post-stroke applications.

4.4. In addition to the biosignal measurement and rehabilitation/assistive systems, is there any other possible implementation of FT in stroke application?

For most patients with stroke, the amount of rehabilitation provided starts decreasing once they leave the hospital. Hence, despite being a great technology for neurorehabilitation acquisition systems and devices, FT can also be used in developing sensors to provide accurate and long-term measurements of several vital parameters that healthcare professionals can remotely analyze. Recent work from Lee *et al* [228] presents the development of a flexible skin-mounted sensing device. It incorporates high-bandwidth triaxial accelerometers and is placed at the suprasternal notch (a visible dip in between the neck). The device can provide real-time recordings of respiration rate, swallowing count, talking time, body orientation, heart rate, and sleep quality. In [229], Kim *et al* developed an e-skin (electronic skin) integrated electronic system that can perform wireless sensing of voice, breathing, pulse wave, chewing/swallowing, temperature, and knee movements. The acquired data is transmitted via Bluetooth unit to the smartphone for real-time display. Also, Murphy *et al* [230] designed an upper-body flexible garment with integrated sensors that are able to monitor heart rate and movement-related parameters to evaluate the progression in post-stroke recovery. Hence, such kinds of intermodal sensing systems could be of great importance in post-stroke applications. They can send an overview of the patient's physiological state to the clinician's phones and computers. Consequently, the clinician can take the necessary steps at the right time, which could lead to faster and better recoveries for stroke patients [209].

5. Conclusion

The analysis of post-stroke function is a long process, starting from impairment assessment, rehabilitative training, monitoring recovery, and providing required assistance to perform everyday life activities. With every passing day, the modern era of technological advancement allows to develop new and innovative post-stroke systems with an aim to support the stroke community. Among them, FT is on the rising curve that provides novel solutions to develop compact, portable, user-friendly, lightweight, and wearable healthcare systems for stroke patients. Hence, in this review, different types of FT for developing stroke systems have been presented, including FE, e-textile, and flexible prototype. It has been shown that every FT has its specific application in developing different modules involved in post-stroke systems. FE is widely used in biosignal acquisition electrodes/units. Similarly, e-textile is adopted for developing various electrodes (EEG, EMG, and FES) and assistive devices. On the other hand, a flexible prototype is mainly used to develop soft robotics systems for advanced rehabilitation and assistive purposes. Every technology has its own advantages and limitations that have been described in detail in the manuscript. Finally, the other possible stroke application of FT and its future perspective has also been discussed that can further revolutionize the development of upcoming post-stroke medical systems.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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