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CURRENT STATUS OF ROBOTIC STROKE REHABILITATION AND OPPORTUNITIES FOR A CYBER-PHYSICALLY ASSISTED UPPER LIMB STROKE REHABILITATION

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ABSTRACT

In the last two decades, robotics-assisted stroke rehabilitation has been wide-spread, in particular for movement rehabilitation of upper limbs. Several studies have reported on the clinical effectiveness of this kind of therapy. The results of these studies show that robot assisted therapy can be more effective in recovering motor control abilities than conventional therapy. On the other hand, studies found no significant improvement on motor function abilities of patients. These contradictory results stimulated our research to survey current status of robotics-assisted rehabilitation and to look for advancement opportunities. We developed a reasoning model that help us conduct the study systematically and to consider the four most important aspects, namely (i) the post-stroke pathophysiological status of patients, (ii) the nature of the rehabilitation therapies, (iii) the versatility of the robotic rehabilitation instruments, and (iv) the kind of stimulation provided for patients. Our major finding is that there are strong evidences that the efficacy of robotics-assisted rehabilitation can be increased by motivation and engagement. We concluded that by exploiting the opportunities offered by cyber-physical systems and gamification, a significant improvement of context sensitive engagement can be realized. Our follow-up research will study various implementation opportunities, the affordabilities of various cyber-physical solutions, and influence on patients.

KEYWORDS

Stroke rehabilitation, robotic rehabilitation, rehabilitation program, motivation and engagement, cyber physical system

1. INTRODUCTION TO THE PROBLEM

Stroke is a serious disabling health-care problem observable all round the world [1]. Approximately 16 million people experience a stroke worldwide per year, of which about two-thirds survive [2]. Some 85 percent of stroke survivors recover partially [3], and about 35 percent of them suffer from a major disability [4] [5]. The most common impairment caused by stroke is motor impairment, which can be regarded as a loss of muscle function control, or limitations in limb movements or mobility [6]. Therefore, problem of stroke rehabilitation has got to the focus of both academic research and practical therapy. In their practical work of physiotherapists and occupational therapists are concentrating on the recovery of impaired movement capabilities and the associated functions, especially in the case of patients with the impaired upper extremity. The simple reason is that the lack or limitation of arm-movement heavily influences the activities of daily activities of post-stroke patients, their abilities to take care of themselves, and thus their well-being and social independence [7] [8].

In the context of treatment and rehabilitation, robotic-assisted rehabilitation represents the state of the art in the practice. It was introduced twenty years ago in the developed countries and has been proliferating all over the world, in particular for movement rehabilitation of upper limbs [9]. Numerous rehabilitation robots have been developed and applied in rehabilitation processes. By now, a lot of knowledge and experience has been aggregated concerning their clinical effectiveness [9] [10].

Certain studies argue that less improvement of the functional abilities was achieved after lengthy training processes than expected [9]. This entails that only limited improvements were achieved in the activities of daily living (ADL) of patients. For example, the results obtained by applying the Fugl-Meyer assessment model show that robot assisted therapy is much more effective in recovering motor control abilities, such as motor power, than conventional therapy [9]. On the other hand, studies that used function independence measurement and the Wolf functional ability test found no significant improvement on motor function abilities of patients [11] [12] [13]. In some cases conventional therapy even had greater gains in motor function abilities than robot assisted therapy [11]. These contradictory results can partially be explained by the limitations of movement patterns in the motor exercises offered by the robotic systems compared to exercises involving daily activities. Furthermore, recent findings suggest that maintaining attention and engagement during the learning of new motor skills or the re-learning of forgotten skills are important for inducing cerebral plasticity after neurological impairments [14] [15]. Current robotics-assisted therapies do not place the patients in an immersive training environment, which would be able to motivate the patients' initiative so that their potentials to recover could be developed to their fullest.

Though movement rehabilitation of upper limbs has been in the center of developments and applications, the results achieved so far are only sub-optimal. The objective of this paper is to cast light on the affordances and the limitations of the current rehabilitation instrumentation and approaches, to propose a more effective version of robotics-assisted rehabilitation as a possible solution for eliminating a number of limitations and offering new opportunities for involving patients in the facilitation of their own rehabilitation processes. Section 2 introduces our reasoning model that was applied in the survey of the current state of the art. Both a patient-centered and a rehabilitation-centered classification have been considered in order to be able to end up with a comprehensive and consistent analysis. Four categories of rehabilitation robotics have been identified and used in the analysis of the advantages and the limitations in the context of various stroke patient categories. Section 3, 4, 5 and 6 present the results of the analyses of the identified four categories of rehabilitation robotics and applications. Section 7 and 8 summarize the limitations of the current rehabilitation approaches and identify the opportunities of the cyber-physical solution for rehabilitation, respectively.

2. THE REASONING MODEL USED IN THE SURVEY

To frame our explorative research, we considered a reasoning model that interconnects four main fields of interest. The first one is pathophysiological status of the patients, which focuses on introducing stages of recovery process of the patients and which kind of therapy should be used in each stage. The second one is the nature of rehabilitation therapies, which is from a therapy-centered view introducing different kinds of therapies being used in current clinical rehabilitation process. The third one is versatility of robotic instruments which focuses on the robotic instruments and their programs. Last but not least, there is an aspect focusing on the kind of stimulation provided for the patients , which is an influencing factor of stroke rehabilitation that have not been fully addressed by current robotic rehabilitation. This model is graphically represented in Figure 1. Each of the indicated

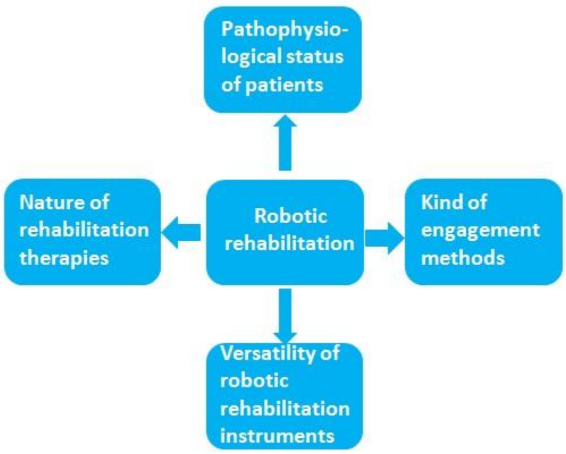

Figure 1 The reasoning model used in this study

fields decomposes to various subfields that have actually formed a platform for, and raised various issues to be considered in our survey and analysis.

Post-stroke pathophysiological status of patients

Normally, (i) acute, (ii) sub-acute, and (iii) chronic states are distinguished in the literature as after-event pathophysiological states of patients. Stroke patients in each stage should receive different therapies and treatments according to their statuses. In Section 3, the status of patients will be introduced, as well as the duration, goal of treatment and therapy of each stage.

The nature of rehabilitation therapies

Besides traditional therapy delivered by physical therapists, there are four main rehabilitation therapies, namely, (i) constraint induced movement therapy (CIMT), (ii) mental practice with motor imagery, (iii) electrical stimulation, and (iv) robotic therapy. In Section 4, we present a concise analysis of these approaches.

Versatility of robotic rehabilitation instruments

Degrees of freedom of the supported movements are as illustrated in Figure 2. Robotics solutions are capable to fully support all 7 degrees of freedom of movement of the shoulder, elbow and wrist. In addition, rehabilitation robotics used in the chronic phase should also involve the movements of hand and fingers. Support of hand rehabilitation requires 16 additional degrees of freedom of robotics solutions. Number of joints that could be exercised is mainly dependent on this.

According to how the robot acts on the intended movements of the patient, control principles for supporting patients with upper limb movement can be categorized into four modes: passive mode, assistive mode, active mode and resistive mode. In passive mode, the robot moves and no intended motion of the patient is needed. In assistive mode, the robot complements the intended motion of the patient. In active mode, patient moves the robot and the robot exert no force. The system could provide human machine interaction for the patients. In resistive mode, the robot delivers force opposite to the intended movement. Usually, these four modes are used in different stages of the patient's recovery.

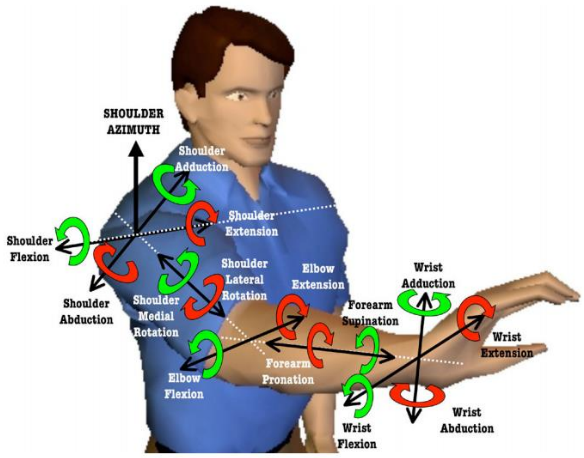

Figure 2 Seven principal degrees of freedom of the human arm (shoulder, elbow and wrist) (adapted from [16]).

Kind of engagement methods provided for patients

There are many kinds of engagement methods which could engage and motivate the patients during training, such as instructions by the physical therapists, virtual reality based rehabilitation, training integrated

Table 1 Description of the stages identified by Brunnstrom

Phase	Brunnstrom's stages	duration	goal of treatment	therapy
acute		post-stroke first week	pain reduction and stabilization of the injured tissue	ensure proper position in bed, turn over every second hour to pat back
sub-acute	stage I: flaccid	post-stroke second week	prevent spasticity	maintain proper position and training in bed
	stages II - IV	post-stroke third week to third month	prevent spasticity and induce correct modes of movement	passive movement, body weight training, trunk control training, and correct abnormal movement
chronic	stages V or higher	post-stroke fourth month - ?	improve ADL, functional ability, and movement coordination	active movement, coordination training, and fine movement training

with video games, etc. In the Section 6, five levels of engagement are listed. Factors that influence motivation will also be discussed, and potential solutions for enhancing motivation during the rehabilitation process will also be identified.

3. POST-STROKE PATHOPHYSIOLOGICAL STATUS OF PATIENTS

As introduced above, three stages could be used to categorize the patients post-stroke. The acute state is around the occurrence of the stroke and typically last not more than a week. The sub-acute state is the beginning of healing. It normally begins in the second week after the event and lasts until the 12th week [17]. It is followed with the chronic state in which intense therapy is applied. The duration of this state in vague, depends on many factors such as heaviness of the stroke, the physical condition of the patient, and the applied rehabilitation therapy.

Based on observing a large amount of hemiplegic patients, Brunnstrom S. proposed to consider six stages of sequential motor recovery after a stroke [18]. The principles implied by this model are to adapt the therapy to the pathophysiological status, to avoid abnormal movements of the patients, and to encourage the correct mode of movement training according to the successive stages. An overview of the stages and the description of the related therapies are shown in Table1.

4. NATURE OF THE REHABILITATION THERAPIES

CIMT is based on the theory of “learned non-use”, which develops during the early stages following a stroke as the patient begins to compensate for difficulty using the impaired limb by increased reliance on the intact limb. This compensation has been shown to hinder recovery of function in the impaired limb [19]. CIMT involves the restraining of the unaffected upper limb and intensively training the affected side with a technique called “shaping”. This therapy is mainly used in the sub-acute phase.

Motor imagery, which has been defined as an active process during which the representation of a specific action is internally reproduced within working memory, without any corresponding motor output [20], is one of the therapies currently applied. It is concluded that conscious motor imagery and unconscious motor preparation share common mechanisms and are functionally equivalent, which may be the reason why mental practice using MI training results in motor performance improvements [21].

Electrical stimulation can be broadly divided into two categories: functional (FES) and therapeutic electrical stimulation (TES). In FES, muscle contraction is provoked in order to assist the performance of functional activities during stimulation. FES is an aid for continuous use. TES, however, is a therapeutic strategy aimed at improving impairments after stimulation. The main application of electrical stimulation for the upper extremity in stroke patients is therapeutically instead of functional [22]. This method could be used in all stages of rehabilitation for post-stroke patients.

Robotics allows patients to train independently of a therapist and to improve upon their own functional level (i.e., robot-assisted therapy). The use of robotic devices in rehabilitation can provide high-intensity, repetitive, task-specific, and interactive treatment of the impaired upper limb and an objective, reliable means of monitoring patient progress. With robotic devices, patients may achieve increased gains from rehabilitation treatment [23].

5. CURRENT ROBOTIC REHABILITATION: ROBOTIC REHABILITATION INSTRUMENTS AND PROGRAMS

Implementation of robotic rehabilitation programs could be divided into fixed rehabilitation program (FRP) and varying rehabilitation program (VRP). FRP means the rehabilitation program is pre-programmed with a limited set of exercises. VRP on the other hand is capable to adapt the rehabilitation program according to the motivation, performance and recovery state of the patients. Moreover, according to the different level of automatism, the VRP could be further divided into simple system and complex system. The former one refers to system, in which the physical therapist changes the program, while the latter one refers to a system, which is capable to monitor different parameters of the patient’s performance and adapt the rehabilitation program accordingly.

5.1 Robotics with FPR

The NeReBot is a 3 degrees-of-freedom (DOF) wire-based robot. In the case of NeReBot, not all 7 DOF of the arm movement can be addressed, since the wires provide only three unidirectional constraints. Also, the working space of NeReBot is rather limited

Table 2 Versatility of the robotic rehabilitation instruments

Current rehabilitation robotics	Rehabilitation program	Degree of freedom	Training mode
NeReBot	Robotics with FPR	3	Passive assist
InMotion2	Robotics with VPR	2	Passive, assistive, active, resistive
Arm Guide	Robotics with VPR	3	Passive assist
MIME	Robotics with VRP	3	Passive assist, active assist, resistive assist, bilateral assist
ArmeoPower	Complex system with VPR	6	Passive assist, active assist

in the horizontal direction [24]. The NeReBot is designed for providing upper limb rehabilitation therapy after stroke during the acute phase. Therefore, the NeReBot focuses on providing passive assist mode [24]. However, because of the characteristic of the wire, which could be pulled but cannot be pressed, it is difficult to provide active mode with this solution for that the system would lose track when the wire is pressed.

In their clinical trial, thirty patients with post-stroke hemiparesis received standard multidisciplinary rehabilitation and were randomly assigned either to robotic training with NeReBot, or used conventional therapy (controlled group). Outcomes were assessed by the same masked raters, with the Fugl-Meyer assessment (FMA) of upper-extremity function, Medical Research Council score (MRC), Motor Functional Independence Measurement (mFIM) and Box and Block Test. The two groups had similar gains on the FMA and MRC, but the control group demonstrated more gains on FIM in both therapy period and the follow-up period [11]. Little improvement in functional ability may be caused by the limitations of the patterns of movements and lack of degrees of freedom.

5.2 Robotics with VPR

InMotion2 Shoulder-elbow Robot

The InMotion2 Shoulder-elbow Robot, which is the commercialized version of the MIT-MANUS (Interactive Motion Technologies, Inc., Cambridge, MA) has two DOF and provides shoulder/elbow training in the horizontal plane with a supported forearm [25]. MIT-MANUS is a planar module which provides two translational degrees-of-freedom for elbow and forearm motion. The two DOF module is portable (390 N) and consists of a direct-drive five bar-linkage SCARA (Selective Compliance Assembly Robot Arm). This configuration was selected because of its unique characteristics of low impedance on the horizontal plane and almost infinite impedance on the vertical axis. These allow a direct-drive back-drivable robot to easily carry the weight of the patient's arm [26].

In one trial, 30 subjects with upper limb deficits due to stroke of at least 6 month duration received 3 week, 18 sessions of robot-assisted therapy conducted by Inmotion2. Results showed little improvement in Wolf Functional Ability [12]. Similarly, there is no difference in Wolf Motor Function Score of 15 individuals between baseline and post-treatment after 3 weeks' therapy with Inmotion2 [13].

This robot can provide only planar motion for the patients, which is not enough for training the movements in daily activities, thus it cannot be used for exercise natural motion of the arm. It may be the reason that accounts for little improvement in functional ability of the patients.

ARM Guide

The ARM Guide aims to provide repetitive movement therapy for rehabilitation after stroke and for assessment of the impairment of the effected arm [27]. ARM Guide is 3 DOF robotic device. A DC servo motor can assist in the movement of a subject's arm in the reaching direction along a linear track [28]. Although it could deliver motor exercise in a three dimensional working space, three degrees of freedom controlled by the system are still not enough to train the whole coordination of the arm movements.

In their clinical test, ten subjects completed twenty-four therapy sessions over an eight-week period. The robot group and the control group showed about the same amount of improvement in the quantitative biomedical measures [29]. Another clinical trial with 19 individuals showed the similar result using ARM Guide [27].

MIME

The MIME is mainly designed for bilateral movement therapy for rehabilitation after stroke [30]. The MIME robot consists of a six DOF robot arm. The robot enables the bilateral practice of a three DOF shoulder-elbow movement, whereby the non-paretic arm guides the paretic arm. The impaired hand and forearm are strapped in an orthotic brace. The brace is attached to the end effector of the robot. An encoder can be used on the arm that is not impaired. This encoder translates the movements of the unimpaired arm to the robot.

In their clinical test utilizing MIME, the subjects were divided into 4 groups, robot-unilateral group, robot-bilateral group, robot-combined group and control group. The robot-combined group (n=10) spent approximately half the treatment time in the unilateral mode and the other half in the bilateral mode. The control group (n=6) received an equivalent intensity and duration of conventional therapy targeting proximal upper-limb function. Proximal FM scores indicated that at post-treatment, robot-combined training group had significantly greater gains than the control group, however, no significant differences were found between the two groups on Functional Independence Measurement (FIM). And gains in robot and control groups were equivalent at the 6-month follow-up. The results also suggest less benefit from the bilateral therapy alone, because this group had the smallest gains in the proximal FM, distal FM, Motor Power exam, and FIM [31]. This is caused by the fact that the active unilateral modes require more focused effort than the bilateral mode so that patients focus more on their affected limb in the unilateral mode than that in the bilateral mode. Therefore, it is better to make the patients engage in motor training of the affected limb only.

5.3 Complex systems with VPR

The ArmeoPower is the commercialized version of the ARMin II by the Swiss company Hocoma [32]. The ArmeoPower consists of a partial exoskeleton with six degrees of freedom that allow for a three dimensional workspace while the base of the device is grounded. The training programs are accompanied by a virtual environment and augmented performance feedback to enhance the motivation. The therapy difficulty can be adjusted to the patient’s progress. The device is impedance controlled. The control system allows for two modes; passive assist and active assist. In the passive assist mode the trajectory, to be performed by the ArmeoPower, has to be recorded by the physician by actively moving the arm of the patient within the device. After the recording the ArmeoPower will repeat the trajectory. In active assist the device provides forces in the movement direction. It adapts the arm support to the individual needs and changing abilities of each patient – from full movement guidance for patients with very little activity to no support at all for more advanced patients. The ArmeoPower precisely records how patients perform and how much support they need during their therapy sessions. Standardized Assessment Tools evaluate the sensors and motors of the device to investigate specific function. The results can be used to analyze and document the patient’s state and therapy progress. Clinical results favor the outcome of therapy with the ARMin II over conventional intensive training [33].

6 KIND OF ENGAGEMENT AND MOTIVATION METHODS PROVIDED FOR THE PATIENTS

6.1 Engagement methods

One of the current endeavors for rehabilitation is to simultaneously increase the engagement and motivation of stroke patients. As mentioned by Brockmyer, J. H. et al., there are different levels of engagement of the users when they are playing video games [34]. We adopt the model and change it to five levels according to rehabilitation training. Different engagement methods are categorized into six aspects, namely, motor, perceptual, cognitive, emotional, social, and hybrid. An analysis of the references shows which level of engagement these methods could achieve.

Action:

It refers to the execution of the task. For example, it may mean passive or active movement of the subject, or completion of an emotional or cognitive task.

Table 3 Engagement methods in different aspects

Engagement methods		Action	Presence	Awareness	Challenge	Flow
Motor	traditional movement exercises	Physical therapy, occupational therapy, speech therapy, eye hand coordination, etc.				
	movement training by robotic based rehabilitation	Passive and active movement training				
Perceptual	visual	[35-38]	[35-38]			
	auditory	[39] [40]	[39] [40]			
	olfactory	[41-44]	[41-44]			
	auditory and visual	[45-54]	[45-54]			
	visual and tactile	[55-59]	[55-59]			
	auditory, visual and tactile	[60] [61]	[60] [61]			
Cognitive	attention	[62]	[62]	[62]		
	working memory	[63] [64]	[63] [64]	[63] [64]		
	reasoning training	[64]	[64]	[64]		
	problem solving	[64]	[64]	[64]		
Emotional	depression	[65] [66]	[65] [66]	[65] [66]		
	fear	[66]	[66]	[66]		
	positive emotion	[67] [68]	[67] [68]	[67] [68]		
	sadness	[69]	[69]	[69]		
Social	cooperation	[70]	[70]	[70]		
	competitiveness					
Hybrid	virtual reality	[45] [46] [49] [53] [55] [57] [59] [60] [61] [62]	[45] [46] [49] [53] [55] [57] [59] [60] [61] [62]	[45] [46] [49] [53] [55] [57] [59] [60] [61] [62]		
	serious (video) game	[61] [71] [72]	[61] [71] [72]	[61] [71] [72]	[61] [71] [72]	[61] [71] [72]
	collaborative tele-rehabilitation	[70]	[70]	[70]		

Presence:

In the context of the paper it expresses either (i) being in a normal state of consciousness, or (ii) having the experience of being inside a virtual environment [34]. In the context of rehabilitation, presence means that the patients lose track of the happenings that are not related to their tasks.

Awareness:

In biological psychology, awareness is defined as a human's perception and cognitive reaction to a condition or event. Therefore, according to the definition, if patients could complete the task which requires a cognitive reaction, then they are aware of what they are performing.

Challenge:

It refers to things that are imbued with a sense of difficulty and victory. If the task is too difficult for the patient due to lack of ability, they could easily become frustrated and quit. Similarly, if the task is not interesting or challenging enough, the patient could become bored. Game elements could change dynamically to maintain an appropriate level of challenge, making the game easier or harder as dictated by the user's performance [72].

Flow:

This term is used to describe the feelings of enjoyment that occur when a balance is achieved between skill and challenge in the process of performing an intrinsically rewarding activity [34]. A specific goal and an immersive performance feedback increase the likelihood of flow [34], therefore, well-designed games can be highly engaging, even addictive, and if they promote limb movement the benefit to the person with stroke could be significant [72].

Literature shows that motoric methods could engage the patients in the action level as far as we found. While with perceptual feedback rehabilitation training could provide the patients with a feeling of presence. It is demonstrated in the current literature that cognitive, emotional and social methods could make the patients aware of the training, which requires cognitive action, emotional change and social communication respectively. Currently, integrating serious game with rehabilitation exercise is the only method could engage the patients to reach the level of challenge and flow. Therefore, the potential opportunities are to look for solutions that could engage the patients to higher level in these five aspects, which will be discussed in the eighth part.

6.2 Motivation factors

Motivation is the purpose or psychological cause of an action. It can be considered a psychological driving force that compels or reinforces an action toward a desired goal. As O'Grady, M. J. at al. analyzed, facilitation of motivation requires technological solutions which are sufficient for the delivery of the required functionality, but which are non-obtrusive [73]. Such technological solutions need to be capable of being subsumed into the fabric of everyday lives of humans. In addition they are supposed to be intelligent, that is, solutions must be capable of evolving to reflect the dynamics of a given condition or indeed the changing needs or circumstances of a given individual. A deployed solution must exhibit sufficient adaptive nature so as to grow with the needs of the individual. Such adaptive nature demands inherent system intelligence, which can be expected from advanced computing solutions only.

The concept of motivation is a common theme in rehabilitation literature [74], and is viewed by many health professionals as being a key factor to the rehabilitation progress [75] [76] [77]. These factors could have an influence on patient motivation for rehabilitation. The first factor is the patients' perception of whether they are able to achieve a successful outcome with the rehabilitation program. The second factor relates to the patient's perceived value of achieving a good outcome with rehabilitation [78] [79]. Finally, allowing the patient to have opportunities for "real choice" in daily activities, such as when, where and how various treatments are undertaken, will increase self-determination. Choice also allows for internalization of control, with control shifting from the health professionals to the patient [79] [80].

Cyber-physical solution for rehabilitation could provide multi-sensory feedback, such as visual, auditory, tactile, olfactory, and even gustatory, to the patients by simulating daily activities. Patients' experience and perception would be enhanced so that they could get a better understanding of the training environment and rehabilitation program. In addition, it is possible for the patients to make "real choices" in this solution. For instance, the patients could select a proper time period for training by reserving a training session in the system. They could also choose the training program or games according to their interests. After the patients finish the exercise or complete the game tasks, the system could give an encouragement to the patients by a score feedback or a report compared with their performance before, so that the patients could gain more confidence and be more motivated to the training.

7 LIMITATIONS OF THE CURRENT APPRAOCHES

7.1 Limitations in the pathophysiological aspect

The evaluation methods of patient's condition are rather subjective. Fugl-Meyer Assessment, the most commonly used assessment method, is based on scales evaluated by the physical therapist [81]. The outcome might be different according to different experience of the physical therapists. Patients who are not evaluated correctly may receive improper treatments which are not beneficial to their recovery. Moreover, not enough effort is conducted to exploit the fullest potentials of the patients.

7.2 Limitations in the aspect of rehabilitation therapy

- Few therapies were found effective in the recovery of functional ability of the patients. For example, in CIMT, it may because the focus of the training is on the strength and power of specific muscle, but not the coordination of the muscles which are used in the daily living activities. As the recovery of stroke patients depends on motor relearning, as a result, the training focusing on training the strength and power of the muscle is not able to re-form the brain with the movement patterns requiring coordination of several muscles. This may also be the theoretical basis that explains why other therapies found little improvement on functional ability either.
- Most therapies only focus on one aspect of rehabilitation, while few could deliver rehabilitation to several aspects, such as motor rehabilitation and cognitive rehabilitation.

7.3 Limitations in the robotic instruments' aspect

- The current robotics based rehabilitation is not able to provide the stroke patients with immersive training environments in which the exercises make the patients feel or think they are doing daily activities in real living context. Therefore, when they are required to complete a certain task in daily life, they cannot use the movement they learned from the motor training assisted by robotics.
- There are limitations on degrees of freedom for most of the current rehabilitation robotics, which limits the possible exercises and complete training of the upper limb, the hand and fingers.
- Not all devices are capable to train fine motoric movements and natural motion patterns. The exercises delivered by these robots focus more on the strengthening of certain muscles than the coordination of several muscles, which is more important in daily activities.

7.4 Limitations in the aspect of engagement and motivation

- Virtual reality methods are still limited in the degree to which they allow users to naturalistically interact with the assessment and rehabilitation challenges presented in a VE. And in order to make persons with cognitive and physical impairments benefit from VR applications, a natural interface that is easy to learn and similar to the real world is required [82]. Besides, many devices that are required to operate a VR system or to track user behavior requires wires and various connectors that are a source of distraction and inconvenience [82].
- Although traditional games have their primary purpose of being compared to popular games that are designed to be fun and engaging, rehabilitation games have not yet fully explored most of the entertainment characteristics games can provide. Thus, further improvements are needed to attain higher levels of motivation for patients in rehabilitation programs [83] [84].

8 OPPORTUNITIES OF COGNITIVELY ASSISTED ROBOTIC STROKE REHABILITATION

The opportunities in these five aspects are listed as following, and illustrated in corresponding blank in Table. 4.

Motor

MOT1: One of the limitations is that not all current devices are capable to train fine motoric movements and natural motion patterns. While in cyber physical system, physical part could move the patient's affected limb in rehabilitation programs. Full degrees of

Table 4 Opportunities for cognitively assisted robotic rehabilitation

	CPS characteristics[85]	Action	Presence	Awareness	Challenge	Flow
Motor	C3: the capability to change the boundaries and behavior dynamically; C4: physical part and cyber part C12: memorize and learn from history and situations	MOT1	MOT2	MOT3	MOT4	
Perceptual	C7: real time information processing capability C10: components obtain knowledge from sensors C11: gather descriptive information and apply context-dependent reasoning		PER1	PER2	PER3	PER3
Cognitive	C4, C7, C10 and C11	COG1	COG2	COG2	COG3	COG4
Emotional	C4, C7, C10 and C11		EMO1	EMO1	EMO2	
Social	C4, C7, C10 and C11		SOC1	SOC1	SOC2	SOC3

freedom could be implemented in order to deliver motor exercises which are similar to natural motion and train not only shoulder and elbow but also hand and fingers. Instead of focusing on training the strength of the muscles, the opportunities of motor training could be focusing on the action and coordination of all the muscles in the affected limb.

MOT2: The current robotics based rehabilitation is not able to provide the patients with immersive training environments. With cyber-physical solution, physical part and cyber part could make a connection among the physical world in which the patient is exercising, the virtual world and the mental world in which the patient is thinking the physical environment. Cognition and awareness is not needed at this level. For example, embedding a passive training in a fun exercise environment could also create presence.

MOT3: Awareness of the physiological capabilities of the patient is of importance to empower them in motoric exercises. Since the patients have deficits in motor and sensory function, they have difficulties in knowing how they are moving and performing a motoric exercise. Cyber-physical solutions could make it possible for the patients to monitor the capabilities of the patient and automatically adapt their rehabilitation programs. In addition, informing the patients about the position, motion of and forces exerted by their affected limb would create awareness of their physical abilities and their improvement. For instance, one opportunity could be sense the force exerted by the patient. Therefore, the patients could know exactly how much force they are able to exert. In this way, the system could also know the potential of the patients.

MOT4: There is a limitation that the current rehabilitation cannot exploit the patients' potentials. Then if the patients are not doing their best, the system will encourage them to making bigger effort instead of assisting them when the tasks are not completed. The rehabilitation programs could be adjusted in the cyber physical systems according to the performance of the patient. If the patient completes the tasks well, then more difficult tasks, such as longer movement distances, larger forces, are supposed to be assigned to them automatically.

Perceptual

PER1: One opportunity of cyber-physical solution for rehabilitation could be providing the patients with multisensory feedback on the physical and virtual world that surrounds them. For example, visual, auditory, tactile, olfactory, and even gustatory sensors can be stimulated, so that the patients could be given a feeling of presence. Information from all the sensors and real time information processing capability of cyber physical systems is of importance to be able to realize task oriented exercises with real world applications (e.g. drinking a cup of tea).

PER2: Empowerment strategy could also be integrated in cyber physical systems. Even if the patients have deficits in some channels of sensory feedback, other channels could be used to help the patients to perceive the real external world. Therefore, the patients could be aware of the training tasks with a training context similar to daily living. This kind of training may have the potential impact on engaging and motivating the patients to a deeper level, and stimulating larger part in the central nervous system with the aim of making the patients to restore the functional ability of the affected limb.

PER3: Persuasion methods used by physical therapists to motivate the patients in conventional therapy could also be implemented in the system. This method could usually encourage the patients and make them more confident so that they could complete more challenge tasks. Besides, this kind of stimulation may have the impact on engaging the patients to enter the state of flow. A training environment with music would also engage the patients by the rhythm of music and affecting their emotion.

Cognitive

COG1: In current rehabilitation, cognitive and motor exercises are handled separately. Cyber physical system could deliver cognitive and motoric trainings together to the patients who suffer from cognitive and motoric deficits due to stroke. The participant will be required to move a physical device to complete cognitive tasks so that the motor and cognitive training are conducted at the same time, which is the opportunity of cyber-physical solution for cognitively assisted rehabilitation.

COG2: In order to train the working memory of the patient, there could be instructions showed on the screen teaching the participant how to organize word lists into meaningful categories and to form visual images and mental associations to recall words and texts. With regards to the training of reasoning, it could focus on the ability to solve problems involving identifying the pattern in a letter of number series or understanding the pattern in an everyday activity such as prescription drug dosing. And for the speed of processing training, it will focus on visual search skills and the ability to identify and locate visual information quickly in a divided attention format [86]. With these training tasks and the feedback from the system, cyber-physical solution for rehabilitation could make it easier for achieving natural human machine interaction, which may solve the limitations of VR methods. In order to complete these tasks, it requires the patients' presence and awareness. Furthermore, with cyber physical system, the attention of the person could be measured by EEG during their cognitive training, which could show their presence and awareness level.

COG3: As discussed above, if the patient could finish the task, then there is an encouragement and the cognitive tasks or games will be more challenging. The pupil dilation could be monitored during training in order to show whether the task is too challenging or boring for the patient of not [87].

COG4: Cyber-physical solution for assisted stroke rehabilitation could easily be integrated with game features. As a specific goal and an immersive performance feedback increase the likelihood of flow [34], well-designed games can be highly engaging, even addictive.

Emotional

EMO1: Currently, rehabilitation games have not yet fully explored most of the entertainment characteristics games can provide. As discussed above, cyber physical system could integrate game features with the rehabilitation system. Therefore, popular video games or online games could be used to train the patients so as to make the patients more engaging and motivated [84].

EMO2: If the patients complete the game tasks, the system could encourage the patient thereby decreasing the negative emotions, such as depression, fear of pain and shame to move. The access to these real choices also could give the patient positive feeling that the rehabilitation is progressing.

Social

SOC1: Few researches have been done related to social needs of the stroke patients. Loureiro R.C. et al. concluded that more functionally limited the individual, the stronger the need to be independent and to engage in community [70]. It is possible that with cyber-physical solution for assisted robotic rehabilitation, the system could store each patient's performance so that after one patient's training, it could rank this patient among all the patients who take the same exercise as well. This kind of game could motivate and engage the patients by arousing their competitiveness.

SOC2: The competitive training among the patients, or the "rehabilitation match", could challenge the patients to help them exploit their fullest potential.

SOC3: Besides, since the cyber physical system could enable distributed system, the patients also could take the exercise the same time in order to co-operate with each other to complete a task. Cooperation with the other patients and interaction with the system may have the potential to engage the patients into the status of flow.

9 CONCLUSION

We have used a reasoning model that considers four relevant factors influencing stroke rehabilitation: (a) pathophysiological status of patient (b) the nature of rehabilitation therapies (c) robotics solutions for assisting motion in physical space to support motoric rehabilitation, (d) cognitive rehabilitation, motivating and engaging patients for executing rehabilitation exercises. Each aspect of the reasoning model was reviewed and analyzed individually. Limitations of the current rehabilitation and the opportunities of cyber-physical solution for rehabilitation have been identified.

Our major finding is that there is strong evidence that the functional ability of the patients with robotics-assisted rehabilitation can be improved by engaging and motivating the patients in a more immersive rehabilitation context. Cyber-physical solutions offer enormous opportunities for robotics-assisted stroke rehabilitation. We have found that engagement of patients can be addressed from the aspects of motor, perceptual, cognitive, emotional and social trainings. For instance, with integration of gamification into cyber physical system, it is possible to engage the patients by increasing their positive emotions, combining physical rehabilitation with cognitive rehabilitation, and establishing their social interactions with other patients. Exercises focusing on more natural movements and coordination of muscles with multi-sensory feedback aiming to reach a deeper level of engagement could be realized with cyber-physical solutions. Our suggestion for future research is to exploit game-based cyber-physical system-assistance in restoration of functional ability of stroke patients.

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