Error Augmented Robotic Rehabilitation of the Upper Limb
A Review

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Abstract: Objective: To collect and assess the available evidence for the efficacy of error augmentation in upper limb robotic rehabilitation.

Methods: A systematic literature search up to May 2013 was conducted in one citation index, the Web of Knowledge, and in two individual databases: PubMed and Scopus, for publications that utilized error augmented feedback as practice modality in robotic rehabilitation of the upper limb.

Results: The systematic search returned 12 studies that utilized error augmented feedback in trials to unimpaired and impaired individuals suffering from stroke, multiple sclerosis and primary dystonia. One additional study utilizing viscous force fields was included as the authors paid special merit to the effects of the field in directions where the error was amplified. In the studies that met the inclusion criteria two different types of error augmented feedback was used that is, haptic and visual feedback which were used either separately as rehabilitation modalities or in conjunction with each other. All studies but one report positive outcome regardless of the type(s) of feedback utilized.

Conclusions: Error augmentation in upper limb robotic rehabilitation is a relatively new area of study, counting almost nine years after the first relevant publication and rather understudied. Error augmentation in upper limb robotic rehabilitation should be further researched in more practice-intensive studies and with larger trial groups. The potential of error augmented upper limb rehabilitation should also be explored with conditions other than the ones described in this review.

1 INTRODUCTION

Neurological impairments resulting from conditions such as stroke and cerebral palsy are common. For example, stroke affects 150 000 people in the UK each year (2005/2006 S.S.C.A., 2001) and cerebral palsy is the commonest cause of childhood disability in Europe (Reinkensmeyer et al., 2004; Huang and Krakauer, 2009; Weightman et al., 2011). Neurological impairment, resulting from these pathologies, often influences upper limb function causing weakness, spasticity and loss of selective muscle activation. These in turn, cause difficulties with voluntary movements and affect the ability to reach, grasp transport and manipulate objects. Movements in affected individuals are therefore characterized by increased duration, reduced peak velocity, increased variability and fewer straight hand trajectories (Wu et al., 2000).

Improvement in upper limb function can lead to better performance in activities of daily living, increased social integration and can thus produce a better quality of life (Maher et al., 2007; Imms, 2008). Exercise of an impaired limb is known to improve function (Kluzik et al., 1990), with better performance observed with increased time and amount of practice devoted to learning a particular task (French et al., 2007). Traditionally such exercises are monitored by a trained clinical therapist. However, researchers have (recently) begun to investigate the application of robotics as a potential modality to support such rehabilitation.

The paradigm of upper limb rehabilitation robotics is a motivating computer environment, which promotes therapeutic movements of the impaired limb with a powered interface implementing a control algorithm to promote recovery (Prange et al., 2006; Scott and Dukelow,

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2011). Such a system can provide patients with access to rehabilitation protocols, which do not require direct, time demanding, supervision of a clinical therapist. As such they can increase access to therapy with limited additional burden on healthcare provision. Furthermore, such systems enable the logging of valuable data regarding user's activity and performance for the therapist to closely monitor adaptation and provide feedback on progress to the user. Rehabilitation robotic therapy has demonstrated statistically significant benefits in improving upper limb function, with kinematic analysis revealing benefits in movement time, path and smoothness of reach (Fasoli et al., 2008; Huang and Krakauer, 2009; Fluet et al., 2010, Weightman et al., 2011, Norouzi-Gheidari et al., 2012).

Currently, three types of rehabilitation robot have been described: i) end point attachment; ii) multiple point attachment and iii) exoskeletons (Reinkensmeyer et al., 2004; Jackson et al., 2007, Scott and Dukelow, 2011; Weightman et al., 2011). End point attachment robots are limited in that they can only promote desirable trajectories (spatial and temporal characteristics) of the hand and cannot control the corresponding position of the elbow and shoulder. However, they are likely to be more cost effective than multiple point of attachment robots and exoskeletons. Multiple point of attachment robots and exoskeletons can control the full kinematics of the arm (end point, elbow, shoulder) but are usually significantly larger and more expensive and as such are less likely to be utilized outside the clinical environment; for example in home rehabilitation applications where size and price can be significant consideration factors for employing such technology.

The control strategy i.e. the manner of interaction between user and the powered joysticks/robotics, implemented is critical for the promotion of improved upper limb function (Reinkensmeyer et al., 2004; Marchal-Crespo and Reinkensmeyer, 2009) and different control strategies have been utilised in the current literature. Marchal-Crespo et al. (Marchal-Crespo and Reinkensmeyer, 2009) suggested they can broadly be divided into three groups. Firstly, assisting control strategies help to move the impaired upper limb in aiming type movements, this is similar to the "active assist" type exercises utilised by therapists (Marchal-Crespo and Reinkensmeyer, 2009; Weightman et al., 2011). Secondly, challenge based control strategies can make movements more difficult, for example augmenting error between actual and desired trajectory or promoting increased effort (resistance training) from the participant. Thirdly, haptic simulation strategies involve the user practising activities of daily living within a virtual haptic environment (Montagner et al., 2007, Marchal-Crespo and Reinkensmeyer, 2009).

Challenge based algorithms such as, error augmenting, are based on the concept that errors in performance and hence results of aiming and prehensile movements of the upper limb influence motor adaptation (Wolpert et al., 1995; *Patton et al.,* 2006b). These strategies have been shown to improve motor function in adults suffering from stroke (Morris et al., 2004; Patton et al., 2006b). Moreover, there have been early indications that error augmented visual feedback can induce motor learning in able bodied and possibly in impaired individuals (Wei et al., 2005). In the last twenty years, substantial work has been done in robotic rehabilitation. Error augmentation seems to be a relatively new modality and to our knowledge there has not been an attempt to gather and collectively report the findings of such studies. Therefore, the purpose of this paper is to present a systematic literature review of research regarding the use of error augmented feedback in the robotic rehabilitation of the upper limb and determine its potential for promoting improved upper limb function in those who have suffered a neurological impairment.

2 METHODS

A systematic literature search up to May 2013 was conducted in one citation index, the Web of Knowledge, and in two individual databases: PubMed and Scopus. In order to ensure that the search would return as many results as possible two different sets of keywords were used in each database. No lower end in year was used in any search. The keywords for the first set were: robot, rehabilitation, upper, limb, error and the keywords for the second set were: rehabilitation, upper, limb, error. Papers identified in either search were included for further investigation. To make sure that significant publications were not missed during the initial search the references of the retrieved studies were checked for relevant publications. After identifying and excluding duplicates, all abstracts were reviewed and when necessary a full review of the manuscript was undertaken.

The inclusion criteria for the review were studies i) with upper limb robotic rehabilitation; ii) utilizing error augmentation as a training modality, including all types of distorted feedback (haptic or visual); iii) where trials on humans (impaired or able bodied) were performed. Only papers reporting new experimental data were included, however it should be noted that the systematic search returned two review papers referring to error augmented robotic therapy in upper limb rehabilitation (Johnson, 2006; Reinkensmeyer, 2009).

3 RESULTS

Out of 60 papers originally identified 12 met the inclusion criteria. An exception was made with study (Patton et al., 2006b) which didn't meet the set criteria for the review, because viscous force fields were used in the study not an error augmentation. However, the authors discussed the effects of the treatment in the directions of the movement where error was amplified. As such the study was considered suitable for the purposes of this review and therefore a total of 13 papers were reviewed.

An overview on the contents of the selected papers can be found in Table 1.

3.1 Overview of Selected Studies

Error augmented robotic therapy for the rehabilitation of the upper limb is a relatively new rehabilitation modality, as the first relevant study was undertaken in 2004 (Patton and Mussa-Ivaldi, 2004). Since then publications regarding this subject are published with an average rate of 1.5 publications per year (Figure 1).

3.1.1 Clinical Characteristics of the Participants

All included studies employed human participants for clinical trials. The conditions that were addressed varied significantly, with six studies focusing on upper limb rehabilitation in stroke patients (Patton et al., 2006a; Patton et al., 2006b; Cesqui et al., 2008; Rozario et al., 2009; Abdollahi et al., 2011; Molier et al., 2011), two studies employing participants with multiple sclerosis (Squeri et al., 2007b; Vergaro et al., 2010) and one study (Casellato *et al.*, 2012) employing error augmented robotic therapy in children with primary dystonia. Furthermore, four studies experimented in the effects of error augmented robotic therapy with the participation of only able bodied, healthy adults (Patton and Mussa-Ivaldi, 2004; Matsuoka et al., 2007; Wang et al., 2010; Shirzad et al., 2012).

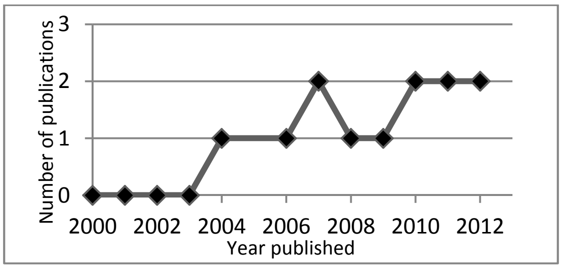

Figure 1: Number of publications on error augmented robotic therapy on the upper limb.

3.1.2 Types of Rehabilitation Robots

Interestingly all but two (Patton et al., 2006b; Molier et al., 2011), studies used single point of attachment robotic systems (endpoint). In one study two endpoint robotic devices were utilized to control the thumb and the index finger of the participants in pinching movements (Matsuoka et al., 2007) while in another study a multiple point of attachment system (exoskeleton) was used for the control of arm movements (Molier et al., 2011).

3.1.3 Types of Error augmented Feedback

Two different types of feedback, where error was augmented, were identified among the selected studies. The approaches can be categorized as: a) Error augmented haptic feedback, where forces perturbed upper limb movement when a certain level of error away from the desired trajectory was reached (Patton and Mussa-Ivaldi, 2004; Patton et al., 2006a; Patton et al., 2006b; Squeri et al., 2007b, Cesqui et al., 2008; Vergaro et al., 2010; Abdollahi et al., 2011; Molier et al., 2011; Casellato et al., 2012); b) Error augmented visual feedback, where the visual output of the system was distorted by a factor (ε) in order for the actual distance between the arm and the target, to differ from the one perceived by the user (Matsuoka et al., 2007; Wang et al., 2010); c) A combination of a and b where error in visual and haptic feedback was augmented (Rozario et al., 2009; Shirzad et al., 2012).

3.2 Intervention Modalities

The main concept of the intervention behind all the reviewed studies was that a user was positioned in front of a computer screen while a robotic manipulandum was attached to/held by the participant's upper limb. A target would be displayed while visual feedback about the current position of the arm was provided to the user. The user was asked to perform movements towards predefined targets while the system responded to the users' movement by augmenting any error.

In some of the reviewed studies (Patton and Mussa-Ivaldi, 2004; Squeri et al., 2007b; Cesqui et al., 2008; Vergaro et al., 2010; Casellato et al., 2012) haptic error augmenting algorithms were compared against other types of haptic algorithms namely, error reducing haptic algorithms. Error reducing algorithms are adaptive assistive algorithms which apply forces towards the optimal trajectory when a threshold of error is reached. In the aforementioned studies the two different types of haptic algorithms were either administered to different trial groups or in the same group but in different stages of the trial in order for a comparison between the two training modalities to be feasible. There was one study (Molier et al., 2011) where restraining forces only occurred when a certain amount of error was reached in order to provide position feedback to the user. In this case the forces were turned off when the user didn't exceed a predefined error threshold.

There was great variance in the number of sessions and the total exercise time the participants undertook, among the studies. In several cases the total intervention time was administered in one session (Johnson, 2006; Patton et al., 2006b; Matsuoka et al., 2007; Casellato et al., 2012; Shirzad et al., 2012) while in others the number of sessions varied from a minimum of 2 sessions (Wang et al., 2010; Molier et al., 2011) to a maximum 10 sessions (Cesqui *et al.*, 2008). Moreover, the total time of exercise administered varied significantly from as little as 90 minutes (Shirzad et al., 2012) to as much as 20hours (Cesqui et al., 2008). Additionally, some studies induced a washout component in the practice regime either by including a washout cycle in the practice session where the perturbative forces were gradually removed (Patton and Mussa-Ivaldi, 2004; Patton et al., 2006a; Casellato et al., 2012), or by setting a washout period between trials where no practice was undertaken (Cesqui et al., 2008; Rozario et al., 2009, Wang et al., 2010).

Table 2 provides an overview on the practice schemes administered in the reviewed studies.

3.3 Outcome Measures

The most common clinical measures among the studies that were used to evaluate outcome on stroke patients were the Fugl-Meyer scale, the Modified Ashworth scale for spasticity and the Box and Block test. Other clinical measures used can be found in Table 3. In the above-mentioned studies kinematic data were collected namely, error that is to say the deviation between the actual and desired trajectory, jerk index (Squeri et al., 2007a), Jerk (Teulings') index (Teulings et al., 1997), and strength (Patton et al., 2006a; Patton et al., 2006b; Cesqui et al., 2008; Rozario et al., 2009; Abdollahi et al., 2011; Molier et al., 2011).

Both studies that performed trials in patients with multiple sclerosis (Squeri et al., 2007a; Vergaro et al., 2010) evaluated performance with clinical measures such as Expanded Disability Status Scale (EDSS), Ataxia and Tremor scale, Nine Hole Peg Test, Visual Analogue Scale (VAS) and the Tremor and Activity of Daily Life (TADL) questionnaire as well as kinematic such as, lateral deviation (root mean square value) from the nominal path, movement duration (seconds), symmetry (ration between acceleration and deceleration phases) and smoothness.

Likewise, studies that employed only able-bodied participants used only kinematic measures like error (distance between actual and desired directory, lateral deviation etc.), mean lag (Matsuoka et al., 2007) and times needed assistance. The times needed assistance measure was used in one study (Wang et al., 2010) where visual error augmentation was utilized. In this studies training scheme the system would assist movement only when a threshold in error was reached. In one study (Shirzad et al., 2012) a Self-Assessment Manikin (SAM) affect questionnaire was administered. Finally, in the study where trials on children with primary dystonia were performed (Casellato et al., 2012) only clinical measures were used that is to say, Burke-Fahn-Marsden Dystonia Rating Scale (BFMDRS).

A more detailed overview of the outcome measures used according to condition can be found in Table 3.

3.4 Impact on Motor Learning and Upper Limb Function

Out of the 13 reviewed studies 12 report positive impact on upper limb function, five of which report conclusive results (Squeri et al., 2007a; Cesqui et al., 2008; Vergaro et al., 2010; Abdollahi et al., 2011; Molier et al., 2011) and seven (Patton and Mussa-Ivaldi, 2004; Patton et al., 2006a; Patton et al., 2006b; Matsuoka et al., 2007; Rozario et al., 2009; Wang et al., 2010; Casellato et al., 2012) report inconclusive but positive results (Table 1). Inconclusive results were considered as, those results where the experiment did not have significant statistical power for definitive conclusions to be drawn and the results where the authors couldn't definitively link improvements to the error augmented treatment.

In one study (Shirzad et al., 2012) the authors concluded that there was no significant impact of the intervention on motor learning but when the different training modes employed in the study were compared, motor learning was improved only when haptic error augmentation was combined with visual error augmentation. In the study where a viscous force field were used (Patton et al., 2006b), the authors concluded that significant positive effects were only encountered in the directions where error was amplified.

4 DISCUSSION

In this review 13 studies were qualitatively analysed regarding the effects of error augmented feedback on robotic rehabilitation of the upper limb. The reviewed studies employed error augmented therapy either in the form of haptic or visual feedback or a combination of the two. Trials were conducted on healthy participants or on adult participants suffering from the effects of stroke or multiple sclerosis or children with primary dystonia.

The first identified study utilizing error augmentation in the robotic rehabilitation of the upper limb was published in 2004 (Patton and Mussa-Ivaldi, 2004). In the nine years since this first study by Patton et. al was published we could only retrieve twelve additional studies regarding error augmentation in the rehabilitation of the upper limb.

4.1 Clinical Trial Protocols

The design of the trial protocols implemented in the reviewed studies varied significantly as did the intervention time and group formation. Five of the studies (Squeri et al., 2007a; Cesqui et al., 2008; Rozario et al., 2009; Vergaro et al., 2010, Abdollahi et al., 2011) employed a crossover protocol where the same group was exposed to different training modalities with a two week washout period between the two. Furthermore, six studies used single session trials (Patton and Mussa-Ivaldi, 2004; Patton et al., 2006a; Patton et al., 2006b; Matsuoka et al., 2007; Casellato et al., 2012; Shirzad et al., 2012) with the total practice time spanning from as little as 22 min (Patton and Mussa-Ivaldi, 2004) to as much as 96 min (Patton et al., 2006a). Interestingly, only one study utilized a randomized control clinical trial (RCT) protocol (Patton et al., 2006b).

Although, the reviewed studies have presented positive indications of the benefits of the error augmented robotic therapy to the rehabilitation of the upper limb, many of the authors argue that more conclusive outcomes could have been produced if their studies had larger numbers of participants and provided more sessions with more practice intensive protocols. Furthermore, the design of the trial protocols seems to be a significant factor that influences the trial outcome. As such trials designed under a Random Control Trial (RCT) protocol, where a well-established haptic control algorithm would be compared to an error augmenting haptic algorithm, could potentially provide more definitive results (Dobkin, 2004).

4.2 Error Augmented Feedback in Upper Limb Rehabilitation

4.2.1 Success of Error Augmented Haptic Feedback Trials

By studying the results of the trials that utilized haptic error augmentation one can conclude that the different conditions are affected differently by this modality. Stroke patients seem to be more positively affected by haptic error augmentation exercises as all studies that performed such experiments on stroke patients conclude that the group that received error augmented therapy showed improvement in the function of the paretic limb. However, such a statement cannot be definitively made as from the reviewed studies, the ones that performed trials on participants suffering from primary dystonia and multiple sclerosis were significantly less than the trials on stroke patients. Therefore, the reviewed studies cannot be compared directly in terms of the outcome for individuals with different conditions.

More specifically, studies (Cesqui et al., 2008, Abdollahi et al., 2011; Molier et al., 2011) conclusively report that the patients who received error augmented therapy were positively affected. In study (Rozario et al., 2009) the authors report that while the kinematic measures indicate improvement, clinical measures did not provide any measurable change in the performance and they suggest that results were probably hindered by the small trial group and the small number of sessions. The difference in the outcome of kinematic and the clinical measures may be due to the fact that kinematic measures in most cases provide better responsiveness, that is they are more capable of accurately detecting changes over time, than clinical scales (Sivan et al., 2011), hence are more sensitive detectors of change.

Both studies that employed participants with multiple sclerosis report positive outcomes. Study (Squeri et al., 2007a) concluded that at the end of the sessions the participants exhibited faster, smoother and more symmetric movement. On the other hand, study (Vergaro et al., 2010) presents similar results but did not indicate significant differences on the outcome between error reducing and error augmenting therapy, with the only exception being a reduction in a tremor related clinical measure which occurred only after error augmented therapy. As such, the improvement presented in both studies may be due to the fact that the participants experienced the positive effects of adaptation in a dynamic environment regardless of the conditions applied within that environment.

With regards to children suffering from primary dystonia (Casellato et al., 2012) results indicate improvement in terms of optimal path control which as the authors suggest may be due to a refinement in the existing sensorimotor patterns of the impaired participants rather than due to motor learning. In the trials involving participation of able bodied individuals (Patton and Mussa-Ivaldi, 2004; Shirzad et al., 2012), the participants could adapt their movement to the altered environment. However, in (Patton and Mussa-Ivaldi, 2004) there was no clear difference of the effects of error augmenting therapy when compared to those from error reducing therapy. Finally, subjects in (Shirzad et al., 2012) showed improved in satisfaction, attentiveness and dominance when they were introduced to augmented error conditions despite of the type of feedback where error was augmented, but didn't show improvements on their performance. Both trials utilized a single session training scheme with relatively small number of repetitions that may have not allowed significant changes in motor adaptation to occur.

4.2.2 Success of Error augmented Visual Feedback Trials

The studies that used error augmentation in visual feedback, were significantly less than the ones that made use of error augmented haptic feedback. It should be noted that in three out four studies where visual feedback distortion was used, only able bodied participants were employed as such it is difficult to draw conclusions on whether the results would transfer to the motor impaired.

Nevertheless, only one study (Matsuoka et al., 2007) reports positive outcome when error was augmented in the visual feedback as it allowed a new coordination pattern to transfer to the trials with no feedback distortion and reduced error. Study (Rozario et al., 2009) didn't provide statistically significant results but indicates that for some of the participants', error was reduced when they were exposed to error augmented training.

4.3 Comparison of Haptic Error Augmented Therapy to other Haptic Therapy

In the studies where the performance of haptic error augmented therapy was compared with haptic error reducing therapy (Squeri et al., 2007a; Cesqui et al., 2008; Vergaro et al., 2010) all studies report that there was no clear indication for the prevalence of one approach over the other. An interesting outcome came from the study where viscous force fields were used (Patton et al., 2006b) as the authors conclude that most of the improvement in function occurred in the directions of the field where errors where amplified.

5 CONCLUSSIONS

Error augmentation in upper limb robotic rehabilitation is a relatively new area of study, counting almost nine years since the first relevant publication, and a rather understudied one. Despite the small number of publications that have employed this modality, there are some clear indications about its potential benefits. The evidence gathered from this review indicate that stroke patients received the most benefit from haptic error augmented therapy but no clear conclusions were drawn whether this training modality has significant benefits on stroke patients, over other established modalities such as error reducing or assistive therapy.

We suggest that large scale randomized control trials be undertaken in order to explore the prospects of haptic error augmentation and fully evaluate its effectiveness on upper limb robotic rehabilitation. In these trials error augmented therapy should be compared against other, more established training schemes. Furthermore, we suggest that the impact of error augmented therapy should be explored in conditions that share similar symptoms related to neuromuscular control to stroke, such as cerebral palsy. Understanding the neurological mechanisms targeted by different therapies, in terms of both learning and motor performance, could provide greater insight into their potential efficacy in a range of different pathologies and is an important consideration for future studies. Likewise, we would like to encourage scientists to perform trials on impaired subjects where error augmentation on visual feedback will be implemented as the results of this review indicate that this modality hasn't been researched to its full capacity.

Guidelines on trial design and dose administration for rehabilitation of the upper limb in conditions such as stroke have been presented in literature (Dobkin, 2004). To the author's knowledge, reviews on the outcome measures for robotic rehabilitation of the upper limb in conditions such as cerebral palsy, primary dystonia and multiple sclerosis have not yet been conducted, while one review regarding such measures has been undertaken for the rehabilitation for the upper limb in stroke patients (Sivan et al., 2011).

This review has identified that there is no uniform condition-specific trial design or evaluation protocol as different intervention protocols and different measures have been used in trials with participants of the same condition. As a result of this a comparison between trials and their outcomes is difficult. Adoption of standard outcome measures would enable inter-study evaluation and help to progress this area of research significantly. As robotic rehabilitation of the upper limb is getting more and more accepted by the scientific community as a valid rehabilitation modality, we believe that uniform condition-specific trial protocol guidelines should be established, in order to enable researchers to easily evaluate the outcome of relevant studies in literature and allow them to compare the outcome of their studies against that of others.

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APPENDIX

Table 1: Overview of the contents of the reviewed studies.

Study	**Year published**	**Type of Condition**	**Type of Robot**	**Type of control**	**Type of feedback altered**	**Number of participants (N)** *(E = experimental group C = control group)*	**Time post-stroke (months)**	**Amount of practice**	**Impact on upper limb function**
(Patton and Mussa-Ivaldi, 2004)	2004	n/a	endpoint	error reducing error enhancing	haptic	8 able bodied	n/a	Total movements: 871 (1 session) Total time practiced: 22 min (1 session for 22 min)	positive inconclusive
(Patton *et al.*, 2006a)	2006	stroke	endpoint	error enhancing	haptic	15 impaired E: 12 C: 9	19-132	Total movements: 742 movements (1 session) Total time practiced: 180 min (1 session of 80 min)	positive inconclusive
(Patton *et al.*, 2006b)	2006	stroke	endpoint	viscous force field	haptic	Total: 31 E:27 impaired C:4 able bodied	16-173	Total movements: 834 (1 session) Total time practiced: 57 min (1 session of 57 min)	positive inconclusive
(Matsuoka *et al.*, 2007)	2007	n/a	endpoint (fingers)	n/a	visual	51 able bodied	n/a	Total movements: 920 movements (1 session) Total time practiced: Unknown	positive inconclusive
(Squeri *et al.*, 2007a)	2007	Multiple sclerosis	endpoint	error enhancing error reducing	haptic	4 impaired	n/a	Total movements: 3680 (4 sessions) Total time practiced: 240 min (4 sessions of 60 min)	positive
(Cesqui *et al.*, 2008)	2008	stroke	endpoint	active assistive error enhancing	haptic	15 impaired	n/a	Total movements: Unknown Total time practiced: 600 min (10 sessions of 60 min)	positive
(Rozario *et al.*, 2009)	2009	stroke	endpoint	error enhancing	haptic/ visual	5 impaired	≥6 months	Total movements: Unknown Total time practiced: 240 min (6 sessions of 40 min)	positive inconclusive
(Vergaro *et al.*, 2010)	2010	Multiple sclerosis	endpoint	error enhancing error reducing	haptic	8 impaired	n/a	Total movements: 1992 (4 sessions) Total time practiced: 240 min (4 sessions of 60 min)	positive
(Wang *et al.*, 2010)	2010	n/a	endpoint	assistive	visual	20 able bodied	n/a	Total movements: 50 (2 sessions) Total time practiced: Unknown	positive inconclusive
(Abdollahi *et al.*, 2011)	2011	stroke	endpoint	error enhancing	haptic	19 impaired	6-259	Total movements: Unknown Total time practiced: 360 min (6 sessions of 60 min)	positive
(Molier *et al.*, 2011)	2011	stroke	exoskelet on	none (haptic feedback for error)	haptic	5 impaired	20-51	Total movements: Unknown (2 sessions) Total time practiced: 540 (18 sessions of 30 min)	positive
(Casellato *et al.*, 2012)	2012	primary dystonia	endpoint	null additive force constant disturbing force	haptic	Total: 22 11 impaired 11 able bodied	n/a	Total movements: 55 (1 session)	positive inconclusive
(Shirzad *et al.*, 2012)	2012	n/a	Endpoint	error enhancing	haptic/ visual	10 able bodied	n/a	Total movements: 129 (1 session) Total time practiced: 90 minutes (1 session of 90 min)	no effect

Table 2: Overview of the contents of the reviewed studies.

Study	Number of sessions	Intervention time in a session	Total number of movements in a session	Number of repetitions under feedback distortion *(haptic, visual or both)* generation in a session	Time trained in error augmentation in a session	Washout
(Patton and Mussa-Ivaldi, 2004)	1	21.95 min	871	a) with intermittent perturbations = 298 b) constant exposure = 330 c) random intermittent removal of the force field Total = 748	a) 7.50 min b) 8.33 min c) 3.00 min Total = 18.83 min	75 movements (1.83 min) at the end of the session
(Patton *et al.*, 2006a)	1	95.75 min	742	a) machine learning = 200 b) learning (opposite to the learned forces) = 222 c) aftereffects catch intermittent removal of the force field = 80 d) sane as c = 80 e) same as b = 2 Total = 584	a) 25.00 min b) 30.00 min c) 20.00 min d) 10.00 min e) 0.25 min Total = 85.25 min	50 movements (3.00 min) at the end of the session
(Patton *et al.*, 2006b)	1	57.00 min	834	n/a	n/a	120 movements (8.00 min) at the end of the session
(Matsuoka *et al.*, 2007)	1	n/a	920	a) Index-Thumb-Both (ITB) distortion =120 b) Thumb-Index-Both distortion (TIB) =120 c) Thumb only condition mirroring ITB = 40 d) Thumb only condition mirroring TIB =40 Total = 320	n/a	n/a
(Squeri *et al.*, 2007a)	4	60.00 min	498	a) Robot learning = 120 b) Trial = 120 c) Training and catch trials = 168 Total = 408	approx. 49.00 min	45 movements at the end of the session 2 weeks after 4 sessions before protocol change
(Cesqui *et al.*, 2008)	20	60.00 min	n/a	n/a	60.00 min	2 weeks after 10 sessions before protocol change
(Rozario *et al.*, 2009)	6	40.00 min	n/a	n/a	35.00 min	2 weeks after 6 sessions before protocol change
(Vergaro *et al.*, 2010)	8	60.00 min	498	a) Robot training = 120 b) Subject training = 288	approx. 37.00 min	2 weeks after 4 sessions before protocol change
(Wang *et al.*, 2010)	2	n/a	25	Total = 25	n/a	n/a
(Abdollahi *et al.*, 2011)	12	60.00 min	n/a	n/a	30.00 min	2 weeks after 6 sessions before protocol change
(Molier *et al.*, 2011)	18	30.00 min	n/a	n/a	30.00 min	n/a
(Casellato *et al.*, 2012)	1	n/a	55	a) Null additive force = 15 b) Disturbing force =15 c) Deactivation of additive external force = 15 Total = 45	n/a	n/a
(Shirzad *et al.*, 2012)	1	90.00 min	129	Total = 65	approx. 45.00 min	10 movements at the beginning every training block (5 cycles/session)

Table 3: Overview of the practice administered in the reviewed studies.

Study	Type of control	Type of Condition	Outcome measures	Statistical measurable impact	Author conclusions
(Patton and Mussa-Ivaldi, 2004)	error enhancing	n/a	**Kinematic**: Error, speed	• The subjects' trajectories shifted significantly towards the desired trajectories (p< 0.05)	• Clinical improvement for adaptive therapy • No clear difference between error reducing and error enhancing therapy
(Patton *et al.*, 2006a)	error enhancing	stroke	**Clinical**: Fugl-Meyer, MAS **Kinematics**: Error	• All but one of the treatment groups movements showed beneficial aftereffects • Average reduction in error of –54%, (p < 0.05) • Treatment group, FM scores marginally increased an average of 1.6 (p = 0.06). No such improvement was seen in the control group (p > 0.27).	• The stroke group: movements showed beneficial aftereffects after training (error decreased) that persisted in all but three patients • This persistence was twice as long as for nondisabled people
(Patton *et al.*, 2006b)	viscous force field	stroke	**Clinical**: Chedoke stage of Arm, Elbow modified Ashworth Spasticity scale, F-M	• The after-effect was significant but 26% smaller that the healthy subjects (confidence 95%) • Significant improvements occurred only when the training forces magnified the original errors F(1,13) = 4,29 (p<0.001)	• For movement directions that begin with significant errors, significant improvement occurred only when the training forces magnified the original errors
(Matsuoka *et al.*, 2007)	n/a	n/a	n/a	• The mean total absolute error for at the first training block was significantly different for the last block (p = 0.001) • No significant results for final performance change at the end of the trial (p = 0.99)	• Training under visual feedback allowed new coordination pattern to transfer to no-feedback trials • Feedback distortion changed the amount of error reduced for each finger separately, and altogether • Distorting individual fingers separately (or together) did not affect the overall speed of learning in movement error reduction.
(Squeri *et al.*, 2007a)	error enhancing error reducing	Multiple sclerosis	**Clinical**: MMSE, EDSS, NRS, Scripps', Aswhorth, Ataxia and Tremor scale, NHPT, VAS, TADL **Kinematic**: Max lateral deviation, movement duration, symmetry, jerk index	• First to last session: highly significant (p=0,000027) decrease in duration and significant increase (p=0.031) in speed profile symmetry • Error enhancing vs error reducing: first-last sessions profile symmetry (p= 0.006) and trajectory smoothness (p = 0.05) increased in error enhancing • Decrease in NHPT score overall F(1,3)=42.133 (p=0.007)	• Analysis of motor performance reveals that, at the end of a training session, movements are faster, smoother and have a more symmetric speed profile • Smoothness improved over sessions
(Cesqui *et al.*, 2008)	active assistive error enhancing	stroke	**Clinical**: MSS, MAS, ROM, Mc-Master Stroke Assessment **Kinematic**: Smoothness, accuracy, path length ratio, movements direction variability	• Robotic-aided therapy led to a significant reduction in impairment of the hemiparetic limbs, as shown by the evolution of the MSS and MAS throughout the therapy (no p-value was provided) • Group I: final metric indexes were no different (F=1.61, p = 0.194) • Group II: final metric indexes were significantly different (F=9,46, p = 0.006)	• Post-stroke patients were able to contrast the perturbation field, i.e., they could reach the target, and perform the exercise (varies dependent on the severity of the impairment) • Improvements were higher depending on the admission upper limb severity level
(Rozario *et al.*, 2009)	error enhancing	stroke	**Clinical**: FM, WFMT, FAS, box and blocks **Kinematic**: Range of motion error	• ROM assessment exhibited a floor effect, where subjects that initially demonstrated fairly low reaching errors did not significantly improve their accuracy in reaching to target • ROM test did reduce for three subjects in the error augmented and control treatment groups. • Error for two of the three subjects was significantly decreased following error augmentation treatment compared to control treatment. • Subjects provided with error augmentation during the first phase of treatment produced greater performance improvements • No significant improvement, deterioration, or notable trends were demonstrated with the clinical measures. *(no statistical analysis was performed*	• the two week treatment blocks might not be sufficient to provide any measurable change clinically, small number of subjects (five) is not sufficient to draw any definitive conclusion • control treatment, while not providing error-augmentation, still improved functionality • MS subjects adapt to unfamiliar dynamic environments • Improvements from error measures don't correlate with clinical measures

Table 4: Overview of the practice administered in the reviewed studies (cont.).

Study	Type of control	Type of Condition	Outcome measures	Statistical measurable impact	Author conclusions
(Vergaro *et al.*, 2010)	error enhancing error reducing	Multiple sclerosis	**Clinical**: EDSS and Functional Systems Score, Scripps' ,NRS, Ashworth scale, Ataxia and Tremor scales, NHPT, VAS,TADL **Kinematic**: Lateral deviation, duration, Symmetry, Jerk	• Significant effect of period (F(1,6) = 16.004; p = 0.00283). • NHPT change from baseline (T0) to the end of the treatment (T3), irrespective of the training mode. NHPT score decreased from 61 ± 14 s to 48 ± 20 s, a 24% change (F(1,6) =16.495, p = 0.007); • Ataxia score decreased from T0 and T3, irrespective of the training mode (F(1,6) = 6.1935, p = 0.04725). The decrease occurred during the first four sessions (F(1,6) = 10.500, p = 0.01768); • Tremor: TADL score decreased in the first four sessions, but only with error augmented training (F(1,6) = 14.087, p = 0.00947); • TADL secondary outcome that significantly decreased only in error augmented training (F(1,6) = 14.087, p = 0.00947).	• Adaptive robot training improves upper limb function. • No significant differences- neither short-term (within session) nor long term (between sessions) - between error-enhancing and error-reducing training.
(Wang *et al.*, 2010)	assistive	n/a	**Kinematic**: Times needed assistance, position error	• Significant improvements were observed in both AAN Session and INT Session (p < 0.001) • 19/20 participants needed fewer times of robotic assistance (no p-value provided) • Tracking performances improved with error augmented therapy (p = 0.0014)	• Participants became more capable of executing the task when the visual error augmentation training method had been integrated with the assist-as-needed training method/no statistically significant difference in carryover effects was observed between the two groups
(Abdollahi *et al.*, 2011)	error enhancing	stroke	**Clinical**: Fugl-Meyer, WMFT, ASFR, Box and blocks **Kinematic**: Rom reach value/rom error	• Six of nineteen subjects showed significant improvement in ROM either immediately following treatment (p = 0.04854) or at the follow-up phase of error-augmented treatment (p = 0.07056) • Error augmentation elicited varied degrees of performance improvement as measured by the AMFM scores based on percentage change from pre-treatment base line values to the follow-up evaluation (95% confidence intervals) • Fugl-Meyer score improved (95% confidence intervals)	• On average, subjects performed better in 1-week follow-up evaluations than they did at the end of the two weeks of training. It may be that the impaired nervous system does not react to nor does it try to learn from smaller errors, and the EA approach may promote learning by simply intensifying the signal-to-noise ratio for sensory systems, making errors more noticeable
(Molier *et al.*, 2011)	none (haptic feedback for error)	stroke	**Clinical**: FMA-UL, Motoricity index MI/ARAT **Kinematic**: Circulant arm movements, isometric strength	• Four subjects improved on the FMA-UL by between 1.0 and 9.5 points. • MI, two subjects improved by 8 and 13 points each • Four subjects improved on the ARAT by between 0.5 and 5.0 points. • Three subjects increased workspace by between 20.2% - 63.4% *(no statistical analysis was performed)*	• Emphasis on errors at the moment they occur may possibly stimulate motor learning when patients perform movement tasks with sufficiently high difficulty levels.
(Casellato *et al.*, 2012)	null additive force constant disturbing force	primary dystonia	**Clinical**: BFMDRS	• Disturbing force affected significantly the movement outcomes in healthy but not in dystonic subjects • In the dystonic population the altered dynamic exposure seems to induce a subsequent improvement, i.e. a beneficial after-effect in terms of optimal path control, compared with the correspondent reference movement outcome (p = 0.05)	• The short-time error-enhancing training in dystonia could represent an effective approach for motor performance improvement, since the exposure to controlled dynamic alterations induces a refining of the existing but strongly imprecise motor scheme and sensorimotor patterns.
(Shirzad *et al.*, 2012)	error enhancing	n/a	**Clinical**: Self-Assessment Mankin questionnaire **Kinematic**: Absolute deviation of trajectory, mean of max deviation	• Increased satisfaction and attentiveness in error augmented therapy and even more in visual and haptic mode (no p-values provided) • the means of each affect measure are significantly different between almost all pairs of conditions (p<0.05) • High-gain visual plus haptic EA leads to a significantly larger amount of learning a, in comparison with both of the visual EA methods (p<0.1)	• Significant differences in effect (specifically: satisfaction, attentiveness and dominance) between progressively more exaggerated error amplification conditions, even when presented in random order to subject