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Anticipatory assistance-as-needed control algorithm for a multijoint upper limb robotic orthosis in physical neurorehabilitation

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ABSTRACT

Robotic devices are becoming a popular alternative to the traditional physical therapy as a mean to enhance functional recovery after stroke; they offer more intensive practice opportunities without increasing time spent on supervision by the treating therapist. An ideal behavior for these systems would consist in emulating real therapists by providing anticipated force feedback to the patients in order to encourage and modulate neural plasticity. However, nowadays there are no systems able to work in an anticipatory fashion. For this reason, the authors propose an anticipatory assistance-as-needed control algorithm for a multijoint robotic orthosis to be used in physical ABI neurorehabilitation. This control algorithm, based on a dysfunctional-adapted biomechanical prediction subsystem, is able to avoid patient trajectory deviations by providing them with anticipatory force-feedback. The system has been validated by means of a robotic simulator.

Obtained results demonstrate through simulations that the proposed assistance-as-needed control algorithm is able to provide anticipatory actuation to the patients, avoiding trajectory deviations and tending to minimize the degree of actuation. Thus, the main novelty and contribution of this work is the anticipatory nature of the proposed assistance-as-needed control algorithm, that breaks with the current robotic control strategies by not waiting for the trajectory deviations to take place. This new actuation paradigm avoids patient slacking and increases both participation and muscle activity in such a way that neural plasticity is encouraged and modulated to reinforce motor recovery.

1. Introduction

1.1. Research context

ABI (Acquired Brain Injury) is defined as an injury to the brain that has occurred after birth but it is not related to congenital defects or degenerative diseases (Brain injury association of america, 2012). The WHO (World Health Organization) estimated that in 2005, stroke accounted for 5.7 million deaths worldwide, equivalent to 9.9% of all deaths, and it was the main cause of disability, afflicting 30.7 million people (World health organization, 2012). These days, nine million people suffer from a cerebrovascular disease every year in the world (World health organization, 2012) and globally, stroke is the second leading cause of death and the eighth cause of severe disability in the elderly. By the year 2020, as the WHO predicts, it will be among the ten most common causes of disability in the developed world. These injuries, due to their physical, sensory, cognitive, emotional and socio-economic consequences, considerably change the life of both the patients and their families. The cause of ABI can be either traumatic (car accidents, falls, etc.) or non-traumatic (strokes, brain tumors, infections, etc.). The most common ABIs are stroke and TBI (Traumatic Brain Injury) (Murray & Lopez, 1997).

New techniques of early intervention and the development of intensive ABI care have noticeably improved the survival rate (The internet stroke center, 2012). However, in spite of these advances, brain injuries still have no surgical or pharmacological

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Abbreviations: ABI, Aquired Brain Injury; ADL, Activity of the Daily Life; BCI, Brain Computer Interface; C, Pearson Correlation Coefficient; DH, DenavitHartenberg; DoF, Degree of Freedom; EMG, Electromyography; IK, Inverse Kinematics; MLP, Multilayer Perceptron; RMSE, Root Mean Squared Error; TBI, Traumatic Brain Injury; WHO, World Health Organization.

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treatment to re-establish lost function. Neurorehabilitation therapies address this problem by restoring, minimizing or compensating the functional alterations in people with disabilities of neurological origin. Medical evidence in neurorehabilitation is scarce and the assessment methods, especially those dealing with upper limb function, depend on clinician experience and subjectivity. Moreover, motion analysis assessments, which are more sensitive and provide objective data, are mainly centered on gait analysis, whereas upper limb tests are still not widely performed; current trend in development towards individualised and more complex models needs to be justified by demonstrating their ability to answer questions that cannot already be answered by existing models (Bolsterlee, Veejer, & Chadwick, 2013). Besides, the lack of standardized protocols due to the large variety of movements, complexity of the upper extremity and lack of international consensus to validate the protocols hampered the advance on this area (van Andel, Wolterbeek, Doorenbosch, Veeger, & Harlaar, 2008).

One of the main objectives of neurorehabilitation is to provide patients with the capacity to perform specific ADL (Activity of the Daily Life) required for an independent life, taking into account that continual practice of fundamentally inappropriate compensatory strategies may be a critical factor limiting recovery after brain damage (Carr & Shepherd, 1989; Davies, 1990). Although traditional physical therapy can enhance functional recovery after stroke, robotic devices may offer more intensive practice opportunities without increasing time spent on supervision by the treating therapist (Dobkin, 2004). This, along with the assertion that traditional therapies are expensive and likely dosage dependant, have caused a remarkable increase in research aimed at creating, controlling and using robotic devices (Conesa et al., 2012; Wolbrecht, Chan, Reinkensmeyer, & Bobrow, 2008).

1.2. Related work

Robotic neurorehabilitation is attractive because of its potential for easy deployment, its applicability across a wide range of motor impairment and its high measurement reliability and thus, there is an increasing interest in using these devices to support neurorehabilitation therapies (Riener, Nef, & Colombo, 2005). Moreover, it is also believed that robotic therapy during the acute and sub-acute phase of stroke recovery could augment changes in impairment driven by spontaneous biological recovery processes (Huang & Krakauer, 2009).

To provide patients with ADL-based functional rehabilitation under the assistance-as-needed paradigm (Emken, Bobrow, & Reinkensmeyer, 2005) (which means to assist the subject only as much as is needed to accomplish the task) and without the presence of a therapist but under his/her supervision, is one of the main challenges of the current neurorehabilitation technologies. Current assistance-as-needed strategies face one crucial challenge: the adequate definition of the desired limb trajectories regarding space and time that the robot must generate to assist the user during the exercise (Belda-Lois et al., 2011).

Rehabilitation robotic control algorithms can be grouped according to the strategy taken to facilitate motor recovery: assisting, challenge based, haptic simulation and non-contact coaching (Marchal-Crespo & Reinkensmeyer, 2009). Assistive controllers actively help the patients to achieve certain goals; challenge-based ones provide resistance to the performed movements. Haptic simulation consists in practising ADL movements in virtual environments. Coaching robotic systems do not physically interact with the patients but provide them with help and motivation.

Besides, there is a scientific theory, called the "Slacking Hypothesis", that suggests that active guidance may decrease motor learning because, in some cases, it can cause patients to decrease their own effort during the training session (Wolbrecht et al., 2007). Thus, assistance-as-needed neurorehabilitation paradigm, which consists in providing the patients only with the assistance they need to perform certain activity, appears as a strong alternative to enhance the therapy outcomes. This actuation paradigm has been proven to be successful in previous motor rehabilitation studies (Barbeau & Visintin, 2003).

Several approaches to the assistance-as-needed paradigm can be found in the scientific literature. Some robotic systems provide an assistance that is proportional to the deviation of the patient given a predefined trajectory. Well known examples of this control strategy are MIT-MANUS (Krebs, Hogan, Aisen, & Volpe, 1998, 2003; Krebs & Volpe, 2013), MIME (Lum, Lehman, & Reinkensmeyer, 1995; Lum, Burgar, Shor, Majmundar, & Van der Loos, 2002; Lum et al., 2006), GENTLE/G (Loureiro & Harwin, 2007), ARMin (Nef, Mihelj, & Riener, 2007; Gijbels et al., 2011; Guidali et al., 2011), L-EXOS (Montagner et al., 2007; Frisoli et al., 2012), ReoGo (Bovolenta, Sale, Dall'Armi, Clerici, & Franceschini, 2011) or NeReBot (Rosati, Gallina, & Masiero, 2007). Other systems that apply the aforementioned control strategy are also (Denve, Moughamir, Afilal, & Zaytoon, 2008; Hesse, Schulte-Tigges, Konrad, Bardeleben, & Werner, 2003; Richardson, Jackson, Culmer, Bhakta, & Levesley, 2006; Toth, Fazekas, Arz, Jurak, & Horvath, 2005; Tsagarakis & Caldwell, 2003). These assistive robotic therapy controllers focus on the following idea: when the subject moves along a desired trajectory (and an artificially created virtual tunnel), the robot should not intervene, and if the participant deviates from the desired trajectory, the robot must create a restoring force (Marchal-Crespo & Reinkensmeyer, 2009).

Dynamic control systems, that are able to adapt to the current needs of the patient based on online performance measurements, can be also found in the scientific literature. The basis of these control strategies is to adapt their configuration parameters tuning the system to the subject changing needs. Riener et al. (2005) developed such system for gait rehabilitation by recognizing the patient intention and adapting the level of assistance to the subject's contribution. Regarding the upper limb, inter-session parameter adaptation methods that allow the selection of the working parameters once a previous performance measurement is available can be found (Krebs et al., 2003; Kahn, Rymer, & Reinkensmeyer, 2004). Recently, Guidali et al. developed a method that made the robotic device able to react in real time to the performance of the subject by updating a dynamic model of the upper limb (Guidali, Schlink, Duschau-Wicke, & Riener, 2011); even though this work supposes a clear step forward to the work presented by Wolbrecht et al. (2008) (whose method was movement-specific) their 'assistance-as-needed' strategy is not focused on the provision of anticipatory force-feedback to the patients, in contrast, their aim is to perform an online adaptation of the amount of support depending on the activity. Finally, some assistance strategies introduce a forgetting factor to keep a challenging assistance level for the patient in order to avoid slacking (Emken et al., 2005; Guidali et al., 2011; Mihelj, Nef, & Riener, 2007; Wolbrecht et al., 2007).

Anticipatory control is still a relatively unexplored niche in the field of rehabilitation robotics. No works have been found that try to anticipate patient intention in order to avoid trajectory deviations. However it is worth to mention the work developed by Everarts, Vallery, Bolliger, and Ronsse (2013), who proposed an anticipatoty algorithm to enhance robotic transparency for gait rehabilitation taking advantage of the cyclic nature of the gait; in this work a predictive layer is incorporated to the control architecture to compensate the computational delays, the mechanical response of the robot and the limited bandwidth.

In relation with intention detection, there are several robotic control mechanisms that rely on the information provided by EMG (Electromyography) signals (Lenzi, De Rossi, Vitiello, & Carrozza, 2012; Song, Tong, Hu, & Zhou, 2013). In these works,