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SPECIAL REPORT

ROBOT-ASSISTED REHABILITATION OF THE PARETIC UPPER LIMB: RATIONALE OF THE ARAMIS PROJECT

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Robot ARAMIS (Automatic Recovery Arm Motility Integrated System) is intended to provide the therapist with novel and time/cost-efficient approaches to the rehabilitation of the paretic upper limb after stroke. The system has been designed and implemented based on common experience in rehabilitation and will provide a robot–patient interaction compensating for some intrinsic limitations of traditional treatments. Rationale, technical characteristics and application are described in detail here.

Key words: robot assisted rehabilitation, paresis upper limb, stroke.

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INTRODUCTION

The outcome for patients with motor impairment after stroke has improved significantly over recent decades with the increasing resources and advanced rehabilitation procedures available in developed countries (1–3). Early admission to, and treatment in, dedicated units is crucial for rehabilitation and is favoured by healthcare policies, restricting in time both the permanence in emergency care units and rehabilitation in hospital (4, 5). In the rehabilitation of inpatients, priority is therefore usually given to posture and walking (6, 7), in order to achieve a greater level of independence in activities of daily living (ADL). Treatment of the upper limb is usually postponed, and recovery of its movement and motor control is often incomplete.

Detailed knowledge of the pathophysiological mechanisms regulating the motility and recovery of the paretic arm is still lacking. *Ad hoc* approaches are therefore mandatory for a useful rehabilitation protocol to be devised and for recovery to occur, with requirements that are, to a relevant extent, determined by the peculiar motor organization of the arm and shoulder (8, 9). In addition, adequate tools are needed to test the adequacy and usefulness of any rehabilitation procedure over a wide range of adaptation conditions. Two major strategies, constraint-induced movement therapy (CIMT) (10), and robot-supported rehabilitation (11, 12), have been developed in recent years.

THE ARAMIS PROJECT: A RATIONALE

There are significant functional links between the trunk and lower limbs. Locomotion after paresis becomes possible also due to the early re-organization of brain control of the trunk, often observed as early as 3–4 weeks or less after brain injury (13). Clinical experience indicates that the unaffected lower limb can vicariate the contralateral paretic leg, and this functional tutoring makes locomotion, if not walking, possible (14).

The upper limbs appear, by contrast, to be largely independent of each other. Correct movement would otherwise become impossible when spontaneous motor recovery is interfered with by poorly tractable algo-dystrophic syndromes, dislocation, or intractable pain at the glenohumeral capsule not prevented by early counter-measures. The arms and hands compete with each other to a significant extent and the unaffected upper limb usually takes over, thus excluding the paretic one when bilateral engagement and co-ordination are required for complex motor operations to be carried out. The proximal, but not the distal, upper limb portion receives both ipsi- and contra-lateral inputs from the brain (15). Very early in extra-uterine life, motor control lateralizes to become peculiarly dependent on the contralateral hemisphere motor organization; although functionally silent in normal conditions, ipsilateral control is nevertheless maintained in part. Brain plasticity (16, 17) allows a post-lesional functional re-arrangement to develop and mediates in motor recovery no matter how complete. This process is possible and usually occurs in the 3–4 months after diaschisis, with the potentiality for recovery decreasing over time depending on the lesion and the individual motor organization before brain insult (18). The spontaneous re-arrangement is not driven by functional or evolutionary rules and can lead to unfit patterns responsible for, for example, spasticity, hypotonia or pathological synergies.

In principle, the crural and brachial functional roles in the recovery of the upper and lower limbs should not differ to a significant extent, yet inadequate recovery has markedly different effects. The main functional and evolutionary purpose of the arm is to drive the hand in the subject's own personal space under visual control mediated by the mirror neurone system (19). The functional recovery of the fingers is of limited help when the hand cannot be moved in the competing space with precision and reliability (20). The roles of the shoulder and elbow in recovery are crucial (21, 22); with proximal-to-distal spontaneous recuperation, hand motor recovery is not

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functional without proximal control of its position in space. Besides, the proximal-to-distal progression of the upper limb recovery allows a wide variety of finalized and functionally relevant motor actions under adequate control. Human and animal studies (23–26) suggest alternative methodological approaches, in which the arm and hand are treated in combination to avoid competitive cortical activation due to intensive motor activity (27–29).

ARAMIS: A CONCEPT ROBOT

This functional outline of the upper limb motor organization derives from basic neuro-rehabilitation concepts (30) that have been properly considered in the development of available robotic devices, including ARAMIS (31–33). ARAMIS is a concept robotic system purported to individually characterize the functional impairment and help design the optimal procedures for the upper limb motor rehabilitation in hemiplegic patients. It features 2 symmetrical, computer-controlled, interacting exoskeletons and can execute motor exercises in a virtually unlimited variety of modalities; application in virtual reality set-ups is possible (Fig. 1; detailed technical information is given elsewhere in this special issue). The project is aimed at developing and testing an alternative approach to the traditional rehabilitation of the upper limb.

ARAMIS allows 3 distinct and sequential operations: (*i*) characterization of the residual motor function of the shoulder, elbow and forearm; (*ii*) design of personalized motor training; and (*iii*) measurement and recording of quantitative indices of motor recovery. Force, speed, acceleration and patterns of movement(s), possible synergies or high impedance due to hypertonia are detected; objective measurements are properly stored and made available to the therapist in numerical and graphic formats in real time. Online feedback on the efficacy of the rehabilitation programme tailored by the ARAMIS station and the early detection of interfering motor synergies or spasticity allow implementation of exoskeleton function and adapt the number, modalities, sequence, speed or strength of the exercises. The therapist does not operate directly on the patients, but controls the congruity of the exercises conducted by or with the support of the exoskeleton with rehabilitation schema and the requirements of motor activities augmentation or depression. The physical properties of each subject's motility, such as strength, acceleration, extent or speed of movement, are inferred by the system through qualitative/quantitative measurements of the unaffected upper limb motility (34). The information is transferred under computer control to the exoskeleton engines that drive the contralateral, paretic arm. The rehabilitation programmes usually begin with simple movements, such as flexion-extension or elevation. Sequences of movements of increasing complexity are then made possible for the paretic arm, consistent with both the subject's unaffected motility and peculiar residual motor organization.

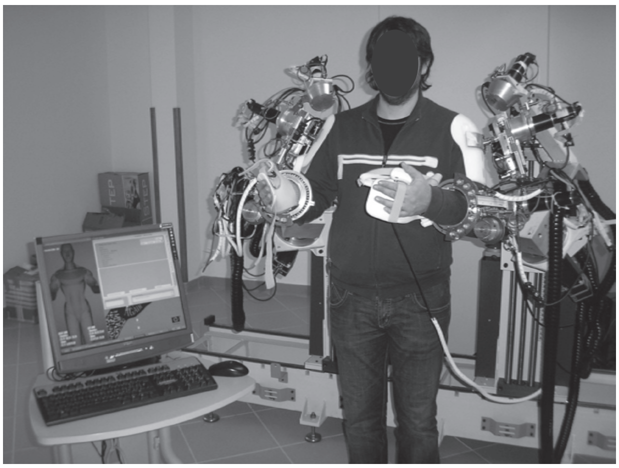

Fig. 1. The robot ARAMIS (Automatic Recovery Arm Motility Integrated System).

Rehabilitation is a learning procedure (35). A paretic arm can recover its motor function after hemispheric damage only if (and to the extent to which) an alternative brain motor organization develops. This re-organization can mimic the system's original properties and needs to be trained consistently with its intrinsic potentialities (36). ARAMIS has been implemented to meet this rationale by adjusting the rehabilitation programme to the newly developed functional arrangement. In all instances, exercises and rehabilitation programmes are made consistent with the residual motor function at any time during treatment (37).

EXPECTED EFFECTS OF ARAMIS

The ARAMIS design is peculiarly based on evidence that the paretic arm recovery progresses from proximal to distal, benefits from the (partly) bilateral innervations of its proximal section, is mediated by brain plasticity on the grounds of pre-existent motor arrangement, etc. Spontaneous functional re-organization is otherwise often anti-economic and may yield abnormalities such as spasticity or reduced muscle tonus. Intense (e.g. 2 h/day) training, beginning within 2 weeks of brain injury and extended in time over 3 months with proper progression, is expected to parallel the early dynamics of spontaneous synaptic re-organization and to favour the development of new motor arrangements consistent with the brain physiological requirements (38, 39). The results should be a better congruency with the physiological neuronal processes and wiring in the brain, neuronal interaction and control economy. The 2-exoskeleton approach should also favour partial or total control from the ipsilateral hemisphere, with enhanced tutoring of a system otherwise inactive in physiological conditions (40). To this end, the sequence and progression of exercises should be designed with due focus on each arm as well as on interaction(s), in order to improve inter-hemispheric transfer of information and inhibit the predominant unaffected arm.

VALIDATION OF ARAMIS

Further investigation on large patients' samples is required for validation. The advantages of ARAMIS in the quantitative characterization of the motor disability, residual function and outcome would help provide shared criteria of evaluation and protocols of rehabilitation, to a final identification of the expected future role and applicability of robotics in neuro-rehabilitation. A study protocol has been approved by the ethics committee and the National Governmental Agencies. Two groups of subjects with hemiparesis due to stroke that occurred, respectively, less than 3 months, or more than 6 months, previously, with age ranging from 18 to 70 years will be admitted to the study. Exclusion criteria will be: implanted pace-maker derivations, aphasia or cognitive impairment not compatible with collaboration, pregnancy, and epilepsy. Systemic or local pharmacological therapies preventing or treating spasticity will not be allowed during the study. Subjects with stroke that occurred less than 3 months earlier will be treated by both conventional rehabilitative methods and treatment controlled by ARAMIS (2×45-min sessions/day for a maximum period of 6 weeks), while those with stroke that occurred more than 6 months earlier will be treated only by ARAMIS-controlled training procedures.

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