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SPECIAL REPORT

THE ARAMIS PROJECT: A CONCEPT ROBOT AND TECHNICAL DESIGN

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Objective: **To describe the ARAMIS (Automatic Recovery Arm Motility Integrated System) project, a concept robot applicable in the neuro-rehabilitation of the paretic upper limb after stroke.**

Methods, results and conclusion: **The rationale and engineering of a state-of-the-art, hardware/software integrated robot system, its mechanics, ergonomics, electric/electronics features providing control, safety and suitability of use are described. An ARAMIS prototype has been built and is now available for clinical tests. It allows the therapist to design neuro-rehabilitative (synchronous or asynchronous) training protocols in which sample exercises are generated by a single exoskeleton (operated by the patient's unaffected arm or by the therapist's arm) and mirrored in real-time or offline by the exoskeleton supporting the paretic arm.**

Key words: robotics, integrated hardware/software system, rehabilitation of the upper limb.

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RATIONALE AND DESIGN

ARAMIS (Automatic Recovery Arm Motility Integrated System) is a concept robot and prototype for the quantitative assessment of disability and residual motor function and the individual tailoring of training protocols in subjects with paretic upper limb after stroke. Based on a rationale developed from current neuro-rehabilitative practice (1–4), the prototype has been designed and engineered in the framework of the project MIMERIC (see Acknowledgements). It comprises 2 exoskeletons with 6 degrees of freedom controlling the shoulder joints (with the first joint (on the axis 1, see Fig. 1) untying the exoskeleton from its supporting structure). The exoskeletons are regulated by 2 engines at an appropriate distance for the patient to wear one or both exoskeleton(s) and for the therapist to manage his or her working space. The cinematic sequence is described in detail in Figs 1 and 2. DC brushed engines, coupled to the axes by planetary gear-heads for best power/size ratio, were designed to meet the movement requirements of the upper limb (5, 6). To this end, a preliminary normative study estimated the average arm weight at approximately 4 kg and length at 300 mm and 250 mm for the proximal and distal arm sections, respectively. The weight of the robot controlled by the main engine is 19 kg, including gear-heads and sensors; the engines positioned at the shoulder, elbow and wrist are designed to parallel the proximal-distal average decrement of the upper limb weight. The system rationale and overall structural/functional architecture are intended to allow the therapist to design individual training programmes compliant with each patient's functional damage and the disability to be rehabilitated (7, 8). The main duty of the robot is to compensate for the inadequate strength and accuracy of the paretic arm and limit the effect of gravity during training. Each exoskeleton can record (*motion capture*) the movements of a sample arm (either the patient's unaffected arm or the therapist's arm) for replication by the patient's paretic arm in synchronous or asynchronous modalities depending on the exercise typology or training programme.

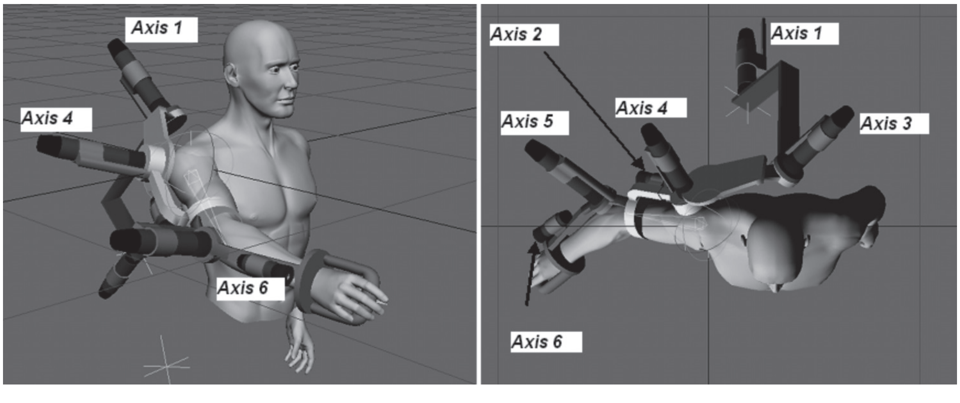

Fig. 1. Automatic Recovery Arm Motility Integrated System (ARAMIS) cinematics.

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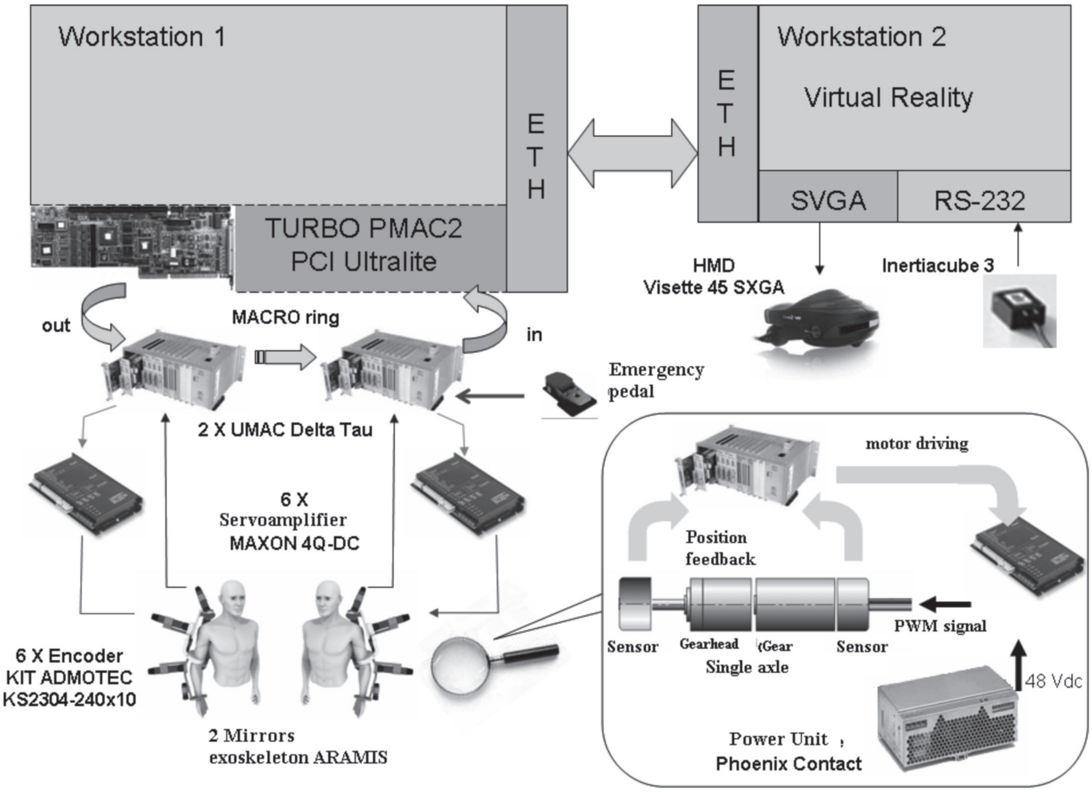

Fig. 2. Hardware architecture of the Automatic Recovery Arm Motility Integrated System (ARAMIS).

Three main training options are available, namely:

- *Synchronous exercises:* the exoskeleton hosting the paretic limb helps replicate in real time the sample movements of the other exoskeleton. In this training modality, sample movements can be provided either by the patient's unaffected limb or by the therapist's arm.
- *Asynchronous exercises:* the robot and patient's paretic arm perform offline sample movements that have been generated previously by the patient's unaffected arm or by the therapist's arm.
- *Training in immersive virtual reality settings,* in training protocols in which the patient works with real-time feedback from virtual 3D scenarios including his or her virtual arm and sample replicas of his or her real world. The therapist can implement the geometry and motor/sensory interaction in virtual reality exercises by means of a 3D advanced editor.

HARDWARE

The ARAMIS hardware architecture (Fig. 2) makes use of 2 workstations (hereafter referred to as WS1 and WS2) linked through Ethernet IEEE 802.3 boards and connections, with overall control by the resident DELTA-TAU TURBO PMAC2 PCI Ultralite board of WS1 also controlling (via the DELTA-TAU Bus MACRO) the DELTA TAU UMAC systems (Delta TAU Data Systems Inc., Chatsworth, CA, USA) responsible for the exoskeletons real-time control. WS2 is the dedicated interface with the devices to be used when exercising in immersive virtual reality and includes a head-mounted display Visette 45 SXGA (Cybermind Interactive Nederland, Maastricht, The Netherlands) (connected through SVGA to the dedicated graphic board) and a position-tracer Inertiacube 3 (InterSense Inc., Billerica, MA, USA), with RS-232 connection.

ARAMIS is operated by 2 UMAC systems. Each system operates one exoskeleton and features two interface ACC-24E2A modules. Each module controls 4 axes, provides the driving signals to the servo-amplifiers MAXON 4Q-DC and can collect/store in proper formats the feedback signals generated by the paired encoders on each joint. The servo-amplifiers supply pulse width modulation power to the exoskeletons engines and the machine can be stopped by means of a push-button linked to the UMAC axes at any time and in each configuration of use in case of emergency. The system motion control and architecture use a high-performance control board with distributed interfaces, hereafter indicated in the diagrams as UMAC Station 1 (left arm) and UMAC Station 2 (right arm). An array of MAXON 4Q-DC Ads-50/10 (1 per joint) allows the interface axes output to be adapted to the power level requirements of the DC brushed engines. The arrangement provides the control of engines with 10 A maximum power absorption in each of 4 work quadrants, with clockwise/counterclockwise movements in each engine/generator modality. For every joint system, a Tacho HEDL 5540HEDL series encoder with 550 pulses and line driver rs422, mounted for every motor by Maxon Electronics (Kansas City, US), is placed upstream of the shaft motor gear system, while an encoder KS2304-240x10 is integrated downstream. The virtual reality hardware includes a helmet with stereoscopic HMD Visette 45 SXGA and an Inertiacube 3 tracer of the head movement mechanically linked to the HMD. Inertiacube 3 is a hybrid 3-degree of freedom tracing device with accelerometers, magnetometers, angular speed detectors, and algorithm combining data to provide information about heading, pitch and roll in the 3 degrees of freedom.

The UMAC system firmware for handling and control can process data and signals and drives the ARAMIS engines in real time. Dedicated, advanced software interacts with the Turbo PMAC2 Ultralite control board, generates its working para meters and is fed back with relevant information on the ongoing training session. The operator sets the working parameters through the ARAMIS Manager software; these are processed by the firmware into distinct control routines that also evaluate the feedback information from the exoskeleton's sensors and feed forward the UMAC devices with signals instructing the exoskeleton's motor patterns. The distribution of the gearheads (1 per joint) does not allow the exoskeleton to move unless engine-driven and a servo-arm has been implemented to link the exoskeleton to the arm. A system with encoder and opposed springs is positioned downstream of each driveshaft and linked out of phase to the main encoder controlling the engine; this allows the exoskeleton to follow the movements initiated by the patient or therapist.

SOFTWARE

The dedicated software has been designed on the basis of the logics and requirements of the neuro-rehabilitative processes that ARAMIS is intended to support (9, 10). Specifically:

- Baseline registration of each patient by demographics, clinical condition, actual motor disability, and expected recovery.
- Individual design of robot-supported rehabilitative protocols.
- Neuro-rehabilitation, with monitoring of the training effects and acquisition/storing of the relevant information on changes in the trainee's motor organization during rehabilitation.
- Up-/downgrading of the training protocols consistent with the achieved recovery or unexpected contingencies (clinical changes, medical problems, side-effects, etc.).
- Offline data analyses.
- Feedback information of potential use in the patient's further training.
- Re-calibration of the training protocols and changes in the rehabilitative strategies congruent with the obtained information.

Four dedicated software modules have been implemented for full system control, with a comprehensive system architecture featuring advance-control connections between framework software, located in WS1 and WS2, logic connections with front-end hardware.

- *ARAMIS Manager:* the main framework module for new patients' registration, access to the patients' database and relevant information needed to plan and carry on the early phases of the rehabilitative protocol. In addition, ARAMIS Manager provides quantitative feedback information and allows control of the exoskeletons and the virtual reality hardware consistent with the training protocol and modalities.
- *EXERCISE Builder:* the module allowing implementation of virtual 3D scenarios for the patient to interact with when trained in virtual reality settings.
- *HMD Interface* is activated when required during virtual reality training. The module implements a 3D rendering engine with 2 input devices and monitors in real time the position in space of the patient's arm and HMD-connected sensors.
- *POSIS:* dedicated software for the analysis of bio-mechanical information obtained by monitoring the training sessions through a 3D player and signal processing descriptors of the patient's motor performance. This tool of the ARAMIS framework is crucial when analysing the early effects of rehabilitation and upgrading the training protocols/modalities.

The contributions of the software modules at different phases of the rehabilitation procedure are outlined in Fig. 3.

DISCUSSION

Robots allow reliable quantitative measurement of physical properties over a wide range of variation, with speed, accuracy, power reliability and endurance over time, and repetitive task conditions that are not achievable by humans. Virtual reality is expected to contribute further (11, 12) to this process. The ARAMIS overall active/passive architecture and exoskeleton multiple-option use in different functional paradigms are expected to compensate, at least in part, for the functional competition between the paretic and unaffected arm, and to promote interaction. The approach should improve the outcome of robot-assisted neuro-rehabilitation compared with conventional training strategies. The purpose of the ARAMIS project is to provide the therapist with a flexible designer of exercises, i.e. a series of software tools able to adapt the machine performance to precise, possibly peculiar, rehabilitation needs. ARAMIS can be used to design training protocols and exercises without predetermined or coded restrictions. The therapist can define a sequence of training movements based on any rehabilitation rationale or methodology by selecting movement, speed and acceleration, with high-accuracy definition in space of the 3D target objects and trajectories with which each patient is requested to comply. The complexity of each exercise and of the training protocol can be increased gradually; to this end, visual stimuli can be calibrated according to the trainee's needs and therapist's strategies before presentation to the patients during training in virtual reality settings. Training protocols, sequence of exercises, the physical characters of each exercise and the patient's errors or improvement during treatment are coded and stored in the database for re-use in the same subject's treatment or to train subjects sharing clinical conditions, disability, and/or training protocols.

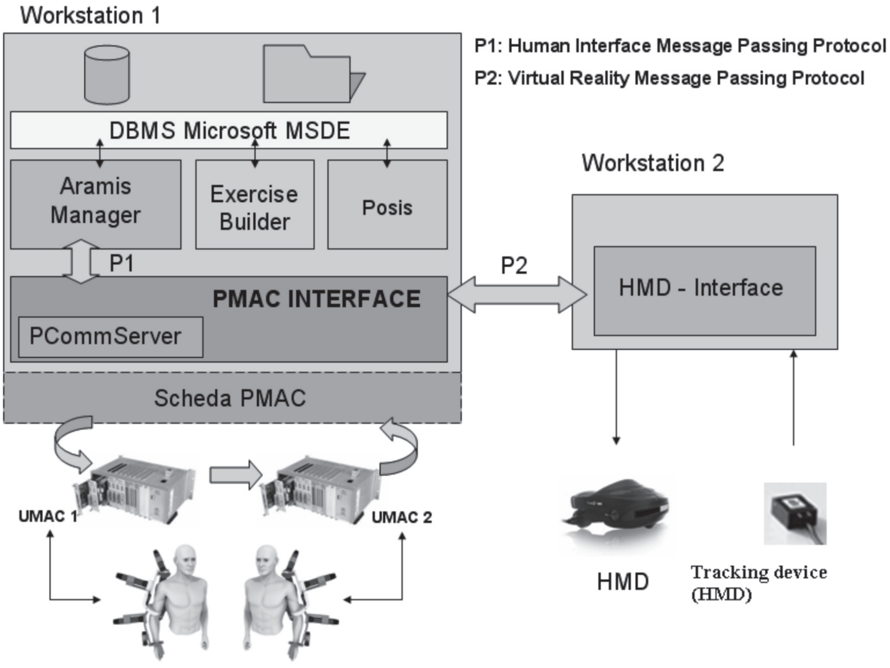

Fig. 3. Framework architecture of the Automatic Recovery Arm Motility Integrated System (ARAMIS).

Comparable arm exoskeletons, such as ARMOR developed by Mayr et al. (13), ARMin developed by Nef et al. (14), MGA Ekoskeleton developed by Carignan et al. (15), UW Prototype III developed by Rosen & Perry (16), and Salford Rehab Exos developed by Caldwell & Tsagarrakis (17) are being developed for the neuro-rehabilitation of the hemiplegic patient with stroke and need to be compared with ARAMIS for optimal implementation. Applicability and suitability of application need to be assessed in clinical studies. To this end, the criteria by which patients are selected need to be scrutinized carefully and chosen to avoid misapplication, in the absence of evidence that the hemiplegic benefit of robot-assisted rehabilitation shares clinical characteristics (e.g. with regard to motor disability and residual motor function) that suggest eligibility for conventional training procedures. Tests on healthy volunteers indicate that ARAMIS ergonomics are acceptable, without problems related to the exoskeleton weight, joints, flexibility of movement in space, etc.

There are many concomitant benefits of robot-assisted rehabilitation. Enhanced patient's interest, dedication to the training, focused attention, and positive cognitive effects should result from training protocols organized at increasing levels of complexity and difficulty, with rewarding feedback information about the subject's improvement during treatment. In principle, robot-assisted rehabilitation should focus the therapist's duties on designing and validating individual training protocols and exercises that the patients can follow under the therapist's control and monitoring, with widespread application, reduced costs, and the possibility of rehabilitation at home under remote control. One result of this would be that neuro-rehabilitation might depend on robot-assisted dedicated systems rather than solely on the availability of expert training staff.

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