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SPECIAL REPORT

ROBOTICS IN NEURO-REHABILITATION

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Objective: **The aims of this study were to review robot-assisted motor and functional rehabilitation of the upper limb in patients with stroke and to outline possible clinical applications of robotics in neuro-rehabilitation.**
Methods: **Available active systems, with actuators driving the paretic arm, were sub-classified by scientific rationale and mechatronic structure as exoskeletons or operational-type machines (manipulators). Applicative studies were compared for indication of efficacy.**
Results and conclusion: **Clinical and biomechanical evidence available to date suggests substantial efficacy of robot-assisted neuro-rehabilitation in the recovery of the paretic arm after stroke, enabling longer dedicated training sessions with no additional work for the therapist. Further investigation of large samples of patients is required to define the relationship between disability and residual function, to provide shared criteria of evaluation of disability/outcome and protocols of rehabilitation, and to identify the expected future role and application of robotics in neuro-rehabilitation.**

Key words: robot therapy, rehabilitation, stroke, upper limb.

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INTRODUCTION

"A robot is a re-programmable, multi-functional, manipulator designed to move material, parts, or specialized devices through variable programmed motions for the performance of a task." Robotics Industry Association (~1980)

"Robotics is the intelligent connection of perception to action." Michael Brady (~1985)

"Robotics is the science and technology of the design of mechatronic systems capable of generating and controlling motion and force." Paolo Dario (~2000)

The neuro-rehabilitation procedures now in use vary in rationale and strategy, with no evidence of differences in their therapeutic efficacy (1, 2).

Training needs to be intensive and prolonged (3, 4); exercises are poorly replicated, and the end-point is difficult for patients to anticipate (5), which may affect patients' drive and commitment. Disabilities, residual motor function and efficacy of treatment cannot be quantified reliably (6), as semi-quantitative evaluation scales are the only established methods to assess motor function and its changes. Each therapist can treat only a single subject at a time, with low effectiveness/costs ratio. In this context, robotic devices (7) appear to be suitable for application under certain conditions and modalities, allowing us to:

- individually adjust the rehabilitative training protocol with due accuracy, replication, and congruity with residual motor function and treatment targets (8);
- quantitatively assess baseline conditions and monitor changes during training;
- acquire knowledge on motor re-organization in hemiplegic subjects (9); and
- extend application with reduced costs by means of rehabilitative protocols performed at home under remote control, with access also made possible to patients who are technology illiterate (7).

Interacting robots and humans compensate reciprocally for their intrinsic limitations while benefitting from peculiar advantages. Robots allow reliable quantitative measures of physical properties over a wide range of variation (10, 11), with levels of speed, accuracy, power and endurance over time that are unachievable by humans. Reliability in the execution of repetitive tasks is high. In contrast, robots lack the flexibility and adaptation, code-independent communication, high-level information processing, and detection of and responsiveness to weak and otherwise undetected significant sensory inputs that characterize humans (Table I).

A robotic system traditionally comprises 5 major components, namely:

- a mechanical structure with degrees of freedom consistent with the tasks to be executed;
- joint-controlling actuators, either electric or pneumatic (for loads in the tens of Newtons), or hydraulic for loads in the range of thousands of Newtons;
- designated ambient, i.e. the space within reach of the robotic device(s);
- sequence(s) of tasks to be executed as detailed by the system computer in suitable language;
- a computer generating the signals that control the robot joints consistent with *a priori* information on the tasks to be executed and knowledge on actual and previous operative conditions and environment.

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Table I. *Comparison between machine and human opportunities and limitations*

	Pros	Cons
Machine	Accurate assessment of physical measures within a wide range of variability Detection of physical measures undetectable to humans (e.g. electromagnetic waves) Speed, accuracy, power Memory storage Endurance with accuracy over repetitive tasks Reliability Possible use in dangerous environments	No "cognitive" abilities or flexibility Limited man/machine communication Inability to respond to unpredicted events Limited identification of salient features and recognition Limited degrees of freedom
Human	High-level cognitive processing and flexibility More degrees of freedom Accuracy in the execution of complex sensory motor tasks Communication irrespective of coded language Insight	Poorly reliable in repetitive monotonous tasks over prolonged periods of time Limited speed and accuracy at high speeds Variable performance depending on condition, motivation, attention, physiological and/or psychological factors/contingencies Errors unavoidable Limited detection of physical quantities Inaccurate memory storage/retrieval

Electromechanical systems, known as mechatronic systems, result from the evolution of robotics and are peculiarly suited for application in neuro-rehabilitation. These are devices or systems with highly flexible mechanic structures working in the external world and their main implements embedded in the structure itself, including:

- actuators;
- source(s) of energy;
- proprioceptive and exteroceptive sensors providing information on the machine functional status and interaction with environment;
- computer single chips processing the signals transmitted by the sensors and instructing the motor controllers;
- man/machine interface(s) receiving information/instructions from users (either the therapist or the patient) and providing online feedback.

Robots can compensate for the patient's inadequate strength or motor control at speeds individually calibrated on the residual motor functions (12, 13), while continuous feedback provides the patient with subjective perception of improvement (14).

These characteristics make robotics a potential support in the rehabilitation domain for both trainers and patients, whose role remains central to the process (15). A variety of sensory, motor and cognitive inputs (16) is needed and can be provided for the system to be operative. These include the patient's subjective control of voluntary movements, (surface) somatosensory inputs, proprioceptive static and dynamic information, pertinent visual information (17) (e.g. in virtual reality or computer games settings), motivation, perception of achievement and reward. In this perspective, motor performance is expected to improve in speed and precision of movement thanks to the repetition of calibrated and replicable exercises in intensive training programmes (18).

The evidence supports application of robotics in neuro-rehabilitation at virtually any level of motor impairment and irrespective of the time-lapse after stroke (19), although early treatment results in earlier and better recovery. Working protocols associated with constraint-induced movement therapy procedures, virtual reality or computer games are possible.

ROBOTICS IN NEURO-REHABILITATION

The field of robotics for neuro-rehabilitation has developed in parallel with robots for industrial use (20), with greater focus on the treatment of the paretic upper limb after stroke. An orthesis with 4 degrees of freedom, Case Manipulator (21), developed in the USA in 1960 was followed by the Rancho Los Amigos Manipulator (with 7 degrees of freedom; 1962) (21), and the Seamone and Schmeisser system (1974) (22). Two prototypes were developed in Europe in the 1970s, notably the German Heidelberg Manipulator (a multi-task robotic arm with 5 degrees of freedom and pneumatic end-effectors controlled by the therapist) (23) and the French Spartacus (designed to provide patients who have severe injury of the spine and spinal cord with tele-manipulators) (24).

Several projects have developed from these prototypes in the following 2 decades. Among these are:

- Manus Project (Hoensbroek Institute for Rehabilitation, The Netherlands, 1984), a manipulator with 5 degrees of freedom for disabled clerks; a development of the rehabilitation robotics designed for research has been sold commercially by Exact Dynamics since 1990 (25);
- Master Project (French Atomic Energy Commission, Fontenay aux Roses, Saclay and Siege, France, 1985), making use of the RTX robot developed in the UK by the Universal Machine Intelligence Ltd, with a cost/performance balance that assured a significant place in the market (26);
- DeVAR (Desktop Vocational Assistive Robot) (van Der Loos, Palo Alto VA Administration, Palo Alto, CA, USA, 1989), implemented from the industrial robot Puma 260 (27);
- Regenesis Workstation Robot (Neil Squire Foundation, Vancouver, Canada, 1988), with 6 degrees of freedom (28);

- RTX Robot Arm (Universal Machine Intelligence LTD, Oxford, UK, 1986): 38% of robotic systems in use for rehabilitation training in 1989 had been implemented from the RTX (29);
- Handy 1 (Keele University, Keele SteffordShire, UK, 1987), a popular device implemented from the robotic arm Cyber 310 with 5 degrees of freedom (30);
- MoVAR (Mobile Vocational Assitive Robot, Stanford University, Palo Alto, CA, USA, 1986) (31);
- Hadar WorkPlace Adaptations (Samhall-Hadar, Malmö, Sweden, 1988) (32);
- MIT Manus (Massachusetts Institute of Technology, Cambridge, USA, 1991), possibly the most seminal system developed thus far, widely marketed under the trade name In-Motion Shoulder- Elbow Robot (8).

RATIONALE, METHODOLOGIES AND EFFICACY

Several robotic systems have been tested for efficacy and in order to identify the useful robot/patient/therapist interaction in paretic upper limb functional rehabilitation after stroke. Research-dedicated systems are usually classified as passive (without actuators) or active (with actuators driving the paretic arm); systems are sub-classified by their scientific rationale and mechatronic structure as exoskeletons or operational-type machines (manipulators) (Fig. 1).

Exoskeletons are robotic manipulators worn by the operator, with links and joints replicating with due approximation those of the human skeleton (Fig. 2). Three main modalities of use are possible:

- strength enhancement, when greater load and resistance is required in peculiar conditions and the exoskeleton shares the load;
- haptic functions, when the actuators feedback the operator with sensory information on remote motion or tactile perception; and
- motor rehabilitation; in this case, the exoskeleton worn by the subject with disabled upper (or lower) limb compensates for the lack of strength or precision in tasks compatible with the requirements of everyday's life or profession in a formal training programme.

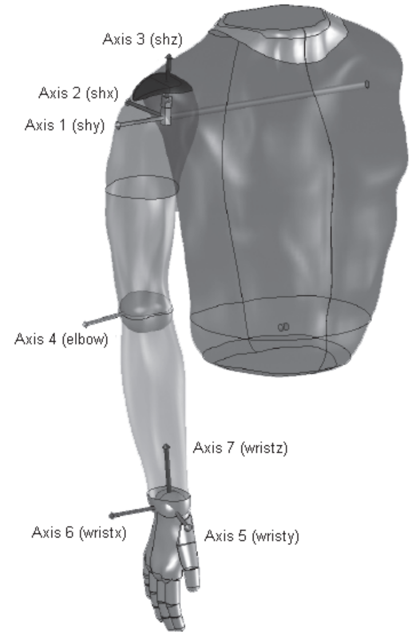

Fig. 2. Links and joints of a robotic manipulator.

To the latter categories belong:

- MULOS System (Scuola Superiore Sant'Anna, Pisa, Italy, 1994);
- Salford Rehab Exos (Salford University, Salford, UK, 1999);
- ARMin (Swiss Federal Institute of Technology, Zürich, Switzerland, 2006);
- Nagoya University system (Nagoya University, Nagoya, Japan, 2003);
- T-WREX (Machines Assisting Recovery from Stroke (MARS) Rehabilitation Engineering Research Center (RERC) on Rehabilitation Robotics and Telemanipulation, Chicago, IL, USA, 2004);
- WOTAS (Wearable Orthosis for Tremor Assessment and Suppression) (Instituto de Automática Industrial, Madrid, Spain and Hôpital Erasme ULB, Brussels, Belgium, 2006);

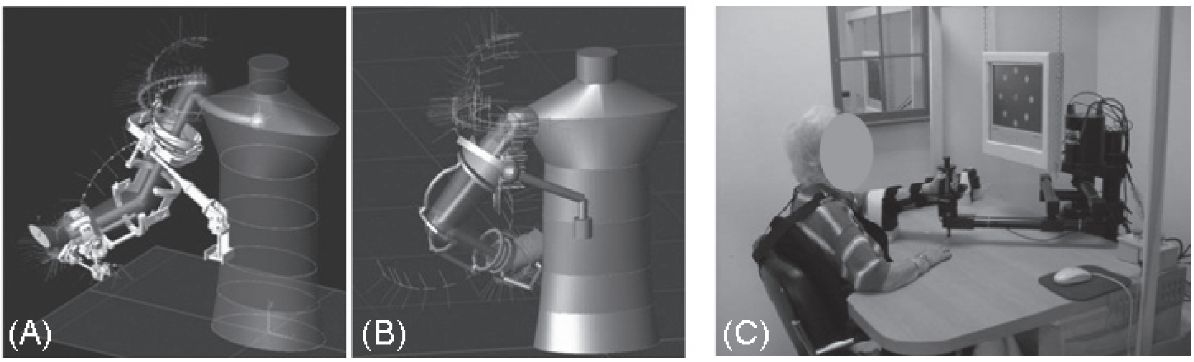

Fig. 1. An exoskeleton representation with related potential degree of freedom (A, B) and an example of operational type machine with training feedback on the monitor (C).

Fig. 3. Examples of exoskeletons.

- MULOS (Motorized Upper Limb Orthotic System) (Centre for Rehabilitation and Engineering Studies, Newcastle, UK, 2001);
- MAHI Exos (Rice University, Houston, TX, USA, 2003);
- L-Exos (Ligth Exoskeleton) (Scuola. Superiore Sant'Anna, Pisa, Italy, 2007);
- the Maryland-Georgetown-Army (MGA) Exoskeleton (Georgetown University, Washington, DC, USA, 2005);
- ARMOR Exoskeleton (University of Maryland, College Park, MD and Georgetown University, Washington, DC, USA, 2007);
- 7 degree of freedom (DOF) Upper Limb Exoskeleton (University of Washington, Washington, DC, USA, 2003).

Exoskeletons offer greater DOF numbers up to 7 active DOF, with guaranteed optimal control of the arm and wrist movement (Fig. 3). However, also in the event of compact and light systems, the motors necessary to enliven the DOF are often conspicuous and require careful and frequent maintenance. Moreover, these systems are difficult to little transport to the patient's home and their use is often restricted to research into the kinematics and dynamics of the human body.

Operational-type machines restrict the patient/machine interaction at the end-effector level (Fig. 4). The system designs for the end-effector trajectories match the hand's natural trajectory in space for the required task. As a result, motor exercises in the real world can be programmed easily; the natural synergy between end-effector and distal (upper) limb determines the functional arrangement of the arm. Operational-type machines have been designed for application to neuro-rehabilitation:

- MIT-Manus (Massachusetts Institute of Technology, Cambridge, USA, 1997) (8);
- ARM-Guide (Assisted Rehabilitation and Measure Guide) (Sensory Motor Performance Program, Rehabilitation Institute of Chicago, Chicago, IL, USA, 2000) (33);
- MIME (Rehabilitation Research and Development Center, VA Palo Alto Health Care System, Palo Alto, CA, USA, 1999) (34);
- Bi–Manual rehabilitators (Research and Development Center of Excellence on Mobility, Department o f Veterans Affairs Palo Alto Health Care System, Palo Alto, CA, USA, 2000) (35);
- MEMOS (MEchatronic system for MOtor recovery after Stroke) (ArtsLab, CRIM Scuola Superiore Sant'Anna, Pisa, Italy, 2005) (36);
- BRACCIO DI FERRO (Neurolab-DIST, Università di Genova and Italian Institute of Technology, Genova, Italy, 2006) (37);
- Robotherapist (Osaka University, Osaka, Japan, 2006) (38);
- GENTLE S (Human Robot Interface Laboratory, Department of Cybernetics and School of Systems Engineering, The University of Reading, Whiteknights, Reading, UK, 2003) (39);
- Nerebot – MAribot (Department of Innovation in Mechanics and Management (DIMEG), University of Padua, Italy, 2006) (40);
- Bi- Manu- Track (Reha-Stim, Berlin, Germany, 2005) (41);
- GENTLE System (Human Robot Interface Laboratory, Department of Cybernetics and School of Systems Engineering, The University of Reading, Whiteknights, Reading, UK, 2001) (42).

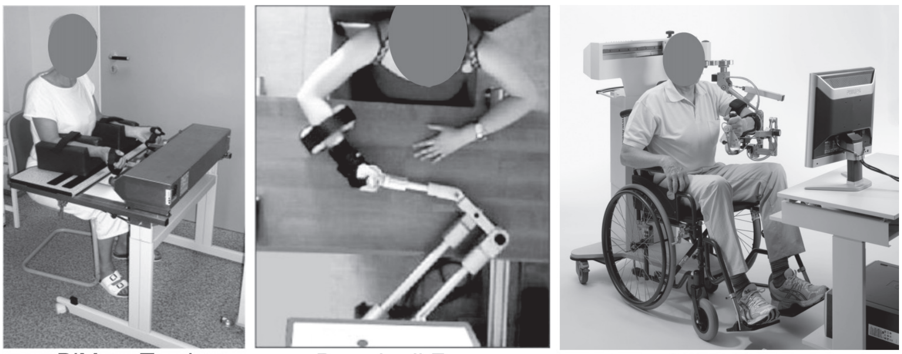

Fig. 4. Examples of operational-type machines.

The best suited devices are the MIT Manus and ARM Guide. MIT Manus is a 2-degree of freedom device for the shoulder and elbow that operates on the horizontal plane with movement at low mechanic impedance for the subject, and supports impaired movements while sensors for strength and position record the trajectory and measure the patient's applied strength. ARM Guide is a 3-degree of freedom device that drives and mechanically assists for strength and precision the patient's reaching movements throughout a linear track, while magnetic fields favour or contrast the movement according to the purposes of the exercise. The system can measure the extent and strength of movement.

COMMENT

Clinical and biomechanical evidence available to date implies substantial improvement of the paretic arm after robot-assisted neuro-rehabilitation, with longer and dedicated training sessions being made possible at no additional work for the therapist. Clinical tests with MIT Manus (8) report improved strength in the proximal upper limb, with reduced motor disability of the shoulder and elbow and smoother movement after training (possibly due, in part, to the robot support in the development of novel alternative motor strategies applicable to everyday life. In addition, treatment helps to prevent complications such as muscular atrophy, spasticity and osteoporosis. A meta-analysis of 10 controlled studies (43) confirmed efficacy in the recovery of everyday motor activities of patients with recent stroke. In several instances, robot-assisted treatment improved motor control more than conventional therapy. However, significant improvement was not observed by the Functional Independence Measure (FIM) or Activities of Daily Living (ADL) scales, and the effects on recovery of the trunk adaptive or compensatory movements (if any) require further investigation. In the meta-analysis (43), 87 studies were identified and screened for retrieval; of these 10 randomized clinical trials involving a total of 218 patients were included in the synthesis. Although many devices have been designed to deliver arm therapy in individuals with stroke, 5 of these devices, the MIT-MANUS, the ARM Guide, the MIME, InMotion2 Shoulder-Elbow Robot (the commercial version of MIT-MANUS, which has 2 degrees of freedom and provides shoulder and elbow training in the horizontal plane with a supported forearm), and the Bi- Manu-Track were tested in at least one randomized controlled trial.

Several critical issues remain unresolved. Specifically, sensorimotor training with robotic devices improves the motor recovery of the shoulder and elbow, apparently without consistent influence on functional abilities, while improvement of the wrist and hand remains limited in subacute and chronic patients. Many studies measure the motor recovery with the Fugl-Meyer assessment scale (FMA) or the arm and hand impairment part of the Chedoke-McMaster Stroke Assessment Scale (CMSA), with the Motor Power Score and the Motor Status Score. Several studies have evaluated functional outcome in activities of daily living using the FIM. Most clinical trials have been carried out with operational-type machines that are currently more applicable to patients' rehabilitation because they are more manageable, easier to transport and require little maintenance. Further investigation on large samples of patients is needed in order to define the relationship between disability and residual function, to provide shared criteria of evaluation of disability/outcome and protocols of rehabilitation, and to make a final identification of the expected future role and application of robotics in neuro-rehabilitation.

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