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The impact of robotic rehabilitation in children with acquired or congenital movement disorders

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Aim. **The aim of this study was to evaluate if the robot-mediated therapy (RMT) can yield positive outcomes in children with acquired or congenital upper extremity movement disorders.**

Methods. **This was an uncontrolled pilot study with pre-post treatment outcome comparison carried out by the Pediatric Rehabilitation Department of a Children's Hospital. The study enrolled 12 children, aged 5 to 15 years, suffering from acquired (at least 12 months post-onset) or congenital upper limb motor impairment. Etiology: 4 stroke, 6 traumatic brain injuries, and 2 hemiplegic cerebral palsy. RMT was provided 3 times a week for an hour during 6 weeks for a total of 18 robot therapy sessions. The Melbourne Scale (MS) and the upper-extremity subsection of the Fugl-Meyer Assessment (FMA) were used for measurement of impairment. Secondary outcome measurements were made through the Modified Ashworth Scale (MAS); the Reaching Performance Scale (RPS); Parent's Questionnaire, and robot-based evaluation measurements. Specifically, authors compared the smoothness, as measured by the jerk metric, and average speed of unconstrained reaching movements.**

Results. **Pre-post clinical evaluation revealed statistically significant gains for all primary and secondary metrics. In addition, significant improvement of robot-based metrics was observed. The primary outcome measurement mean (SEM) gains were 6.71 (1.29) for MS and 3.33 (0.80) for the FMA. RMT led to spasticity decreases in chronic cases, as shown by the reduction of MAS. It led to improved trunk-upper extremity postural attitude as demonstrated by improved RPS, and it was well accepted by parents and children as observed in the Parent's Questionnaire.**

Conclusion. **This study suggests that RMT may hold rehabilitative benefits in children suffering from acquired and congenital hemiparesis.**

Key words: Rehabilitation - Cerebral palsy - Brain injuries - Stroke - Movement disorders.

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Conflict of interest.—Dr. Krebs is a co-inventor in the MIT-held patent for the robotic device used to treat children in this work. He holds equity positions in Interactive Motion Technologies, Inc., the company that manufactures this type of technology under license to MIT.

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Robot-mediated therapy (RMT) has been a very active area of research in recent years and it holds much promise for improved outcomes.[1-3] RMT appears to promote improvement in sensorimotor as well as cognitive processes.[4] The RMT benefits are: 1) it produces a controlled and repeatable therapy experience and 2) it allows quantitative evaluations of kinematics and kinetics to estimate the patient's progress, while traditional clinical scales permit only qualitative evaluations potentially carried out by diverse therapists.[5] RMT can play a relevant role in the rehabilitation of the upper and lower limb of patients affected by congenital or acquired brain injury by means of task specific exercises.[6-13]

Kwakkel has demonstrated that high-intensity and task-specificity are two of the main features of any successful stroke rehabilitation program.[14, 15] Both of these features are ideally suitable for robotics application.[10] Robotics can be programmed to simulate a variety of tasks affording both high intensity and repeatability, similar to stereotypical patterns employed during therapy.[16, 17] Robotic devices may also be employed to impose novel forms of mechanical manipulation that therapists cannot emulate [18] and adapt to patients' performance, assisting them as needed during a given motor task.[19-21] The initial meta-analysis of RMT have shown promising impact of the technology in the rehabilitation of stroke patients.[22-24]

This study evaluate the effectiveness of RMT in children with chronic upper limb motor impairment following congenital or acquired damage motor impairment.

Materials and methods

Subject population

Twelve children with congenital or acquired paresis were engaged in an RMT program. They performed a 1-h session three times a week for 6 weeks involving a robot-assisted upper limb therapy with goal-directed planar reaching tasks. We employed the same sensorimotor training employed with adult stroke.[25-27]

Children were recruited from patients' pool of the Rehabilitation Department of the Children's Hospital "Bambino Gesù" (Rome, Italy) and met the following inclusion criteria: 1) children with hemiplegia; 2) medically stable and able to participate in a robotic therapy program; 3) interval from the acute event >6 months; 4) Modified Ashworth Scale (MAS) ≤3 for each segment; 4) Passive Range of Motion (PROM) >120 for shoulder flexion and abduction, <90 for elbow flexion and >150 for the extension. The exclusion criteria were: 1) pharmacological treatment in the prior six months (*e.g.*, Botox) and 2) visual-spatial deficit.

Subjects' age ranged from 5 to 15 years (mean: 10.5 years) (Table I). Clinical diagnosis included 4 strokes, 6 traumatic brain injuries, 2 hemiplegic Cerebral Palsy. None of the children were engaged in conventional physical therapy programs during trials and were naïve to RMT (*i.e.*, had not received RMT prior to this study).

The experimental protocol was approved by the Ethical Committee at Children's Hospital "Bambino Gesù", where the RMT was provided. Informed and assent consents were obtained from all parents and children.

Apparatus

The InMotion2 robot (Interactive Motion Technologies Inc., Cambridge, MA, USA), a commercial version of the MIT-Manus, was used. This robot was developed specifically for upper extremity neurological rehabilitation and described in detail elsewhere.[1] Because this is an end-effector based robot, no modifications were required to allow its use by small children except to modify the chair size and the hand-holder to fit smaller hands. MIT-Manus is a planar two degrees-of-freedom highly backdrivable (*i.e.* low inertia and friction). During therapy, subjects were seated with the trunk strapped by a 5-point seatbelt to limit forward trunk compensation, and their paretic arm was placed in a handholder attached to the robot end-effector.

The robot sensors permit an accurate and continuous measurement of relevant key variables including position, velocity, and applied forces (sampled at 200 Hz, with accuracies of 0.1 mm and 1.5 mm/s, respectively). A computer screen in front of the child provides online visual feedback of the target location and of the hand movement.

A physical therapist was present at all times to ensure proper positioning of the child and to provide verbal instructions and incentive.

Evaluation

The clinical evaluations were performed at the enrollment and completion of the protocol. It includ-

TABLE I.—*Enrollment demographics.*

	Age (year)	Gender	Pathology	Time since pathology onset	Lesion side	Cerebral loci (RMI)
ID1	12	Female	Stroke	7 year	Right	Parietal lobe
ID2	14	Male	Stroke	8 years	Left	Internal capsule
ID3	16	Male	Stroke	5 years	Right	Parietal lobe
ID4	11	Male	Traumatic brain injury	1 year	Right	Frontal lobe and corona radiata
ID5	9	Male	Traumatic brain injury	3 years	Left	Peri-ventricular and corpus callosum
ID6	5	Male	Traumatic brain injury	6 months	Left	Frontal lobe and thalamus
ID7	15	Female	Traumatic brain injury	18 months	Left	Frnto-temporal lobe and cerebral peduncole
ID8	12	Male	Traumatic brain injury	1 year	Right	Frontal lobe-temporal lobe-cerebellum
ID9	14	Male	Dystonic cerebral palsy	congenital	Left	Peri-ventricular leuco-malacia
ID10	13	Female	Stroke	6 years	Right	Parietal lobe
ID11	7	Male	Dystonic cerebral palsy	Congenital	Left	Peri-ventricular leuco-malacia
ID12	12	Male	Traumatic brain injury	2 years	Right	Frontal lobe

ed: 1) MAS [28] that evaluates the muscle spasticity rating the resistance to passive stretch of shoulder, elbow, wrist muscles; 2) PROM measurement of shoulder, elbow and wrist;[29] 3) the Reaching Performance Scale (RPS) [30] that is a measurement scale evaluating the control of trunk movement and stability during reaching performance; 4) the Melbourne Assessment of Unilateral Upper Limb [31] that is an evaluative tool measuring unilateral upper-extremity quality of movement in children from 5 to 15 years of age; 5) the Fugl-Meyer Assessment [32] upper extremity function that measures upper limb motor impairment, including items related to the presence of synergistic and isolated patterns of movement of the shoulder, elbow, forearm, wrist and hand. In addition, we delivered the Parent's Questionnaire to evaluate acceptability and estimate how the child uses his weaker arm outside of the therapeutic environment.

In addition, the robot recorded unassisted, point-to-point reaching movement during each therapy session. Movement smoothness as an index capable of characterizing the level of motor performance were evaluated. Smoothness appears to be a relevant feature of unimpaired subject's movement. In addition, there is an old conjecture in movement neuroscience that continuous arm movement appears to be composed by discrete submovements.[33, 34] Krebs [34] and Rohrer [35] showed how smoothness and submovement, characteristic of stroke subjects, change with recovery. Smoothness can be characterized via distinct performance indices [35, 36] and we will employ a jerk metric (JM). We defined the JM as the average amplitude of the rate of change of acceleration divided by the average speed (AS). Movement with lower JM typically has fewer submovements (segments).

Intervention

Training consisted of a visually-guided, goal-directed, terminated planar reaching task. Eight targets were equally spaced around a center target (Figure 1) and visual feedback of both target and robot handle location were provided on a computer screen in front of the child. The task required each subject to attempt to move from the center position to a target and then return to the center.[1] Contrary to the training with adults, the targets were block-randomized with each one of the eight possible positions presented an equal number of times. The goal was to increase the child's attention avoiding mnemonic scheme of target presentation.

Each of the robot-assisted modes was preceded and succeeded by an active set of games. The active mode implies that the robot provides no assistance during the task. The child has to move the low inertia, low friction robotic arm to the target. We examined smoothness only during these unassisted reaching movements. In the assisted mode setup, the robot is impedance controlled which modulates its response to mechanical perturbation. It drives the patient's hand toward the target by limiting the movement inside a small region around the path to the target. The assistive setup is generally considered much like conventional "hand-over-hand" type of assistance. The data recorded in this mode was not used to characterize smoothness.

Each robot session was composed by 8 batches.

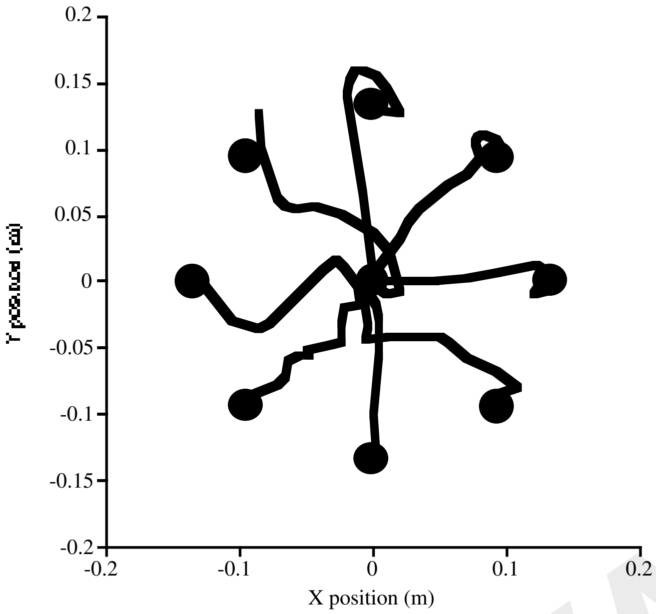

Figure 1.—Trajectories during target set. Example of 8 point-to-point reaching movement traces performed by a child starting at the center towards each outbound target.

TABLE II.—*Comparison of enrollment and protocol completion scores (N.=12).*

Evaluation	Time of the evaluation	Mean±SD	T-student	P	r
MAS/35	Enrolment	9.67±3.14	4.21	0.001	0.3
	Study completion	8.25±3.33			
	Change	1.41±1.16			
Fugl-Meyer/66	Enrolment	36.33±9.50	4.16	0.002	0.8
	Study completion	39.67±10.65			
	Change	3.33±2.77			
Melbourne %	Enrolment	54.38±19.53	5.20	<0.001	0.3
	Study completion	61.1±22.03			
	Change	6.71±4.47			
RPS close	Enrolment	8.67±3.60	3.63	0.004	0.27
	Study Completion	9.67±4.05			
	Change	1.00±0.95			
RPS far	Enrolment	8.67±3.17	2.46	0.032	0.33
	Study completion	9.42±3.57			
	Change	0.75±0.02			
Jerk metric	Enrolment	0.180±0.17	3.35	0.006	0.6
	Study completion	0.066±0.06			
	Change	0.114±0.03			
Average speed	Enrolment	0.083±0.05	3.09	0.010	0.06
	Study completion	0.116±0.06			
	Change	0.033±0.03			

All batches consisted of 96 point-to-point reaching movements along the 8 different targets (4 active batches and 4 robot-assisted batches).

At enrollment and at completion of RMT, a robot-based evaluation was conducted following clinical assessment.

For each child, we evaluate only the movements starting at the center target and terminating at a target outbound, which corresponds to 192 reaching movements of the 384 total (4 batches). We assumed that a movement starts if its speed is greater than a 10 mm/s for 100 ms and ends when the position of the handle is around the target (in a 1 cm radius from the target) for more than 100 ms.

Statistical analysis

Parametric and nonparametric analyses were performed leading to similar results. Student's t test was used to compare change scores from enrollment to protocol completion. Statistical significance was set at P≤0.05. We also calculated Cohen's Effect Size (r) with r <0.10, 0.30, or >0.50 as small, moderate and large effect-size respectively. Trajectories were sampled at 200 Hz and smoothed by using a 6th order Butterworth filter, with a 170 ms window (cut-off frequency: ~11 Hz).

Results

At the completion of the robotic therapy protocol, children were able to move towards all the targets, an observation that is translated into improvement in most clinical scores as shown in Table 2 and Figure 2 . There is a statistically significant, large effect-size for the Fugl-Meyer Assessment (t=4.16, P=0.002, r=0.8) and for the robot-based JM metric (t=3.35, P=0.006, r=0.6). A statistically significant change of moderate effect-size was found for the MAS score (t=4.21, P=0.001, r=0.3), the Melbourne Assessment Scale (t=5.20, P=0.002, r=0.3), the RPS close (t=3.63, P=0.004, r=0.27), on the RPS far (t=2.46, p=0.032, r=0.33). The AS (t=3.09, P=0.010, r=0.06) was also statistically significant. The Parent's Questionnaire reported a high level of satisfaction that revealed a better use of the arm during the activity daily life. Clinically, children were better able to move their paretic arm in reaching movement and to control the synergy and the coordination of shoulder, elbow and wrist.

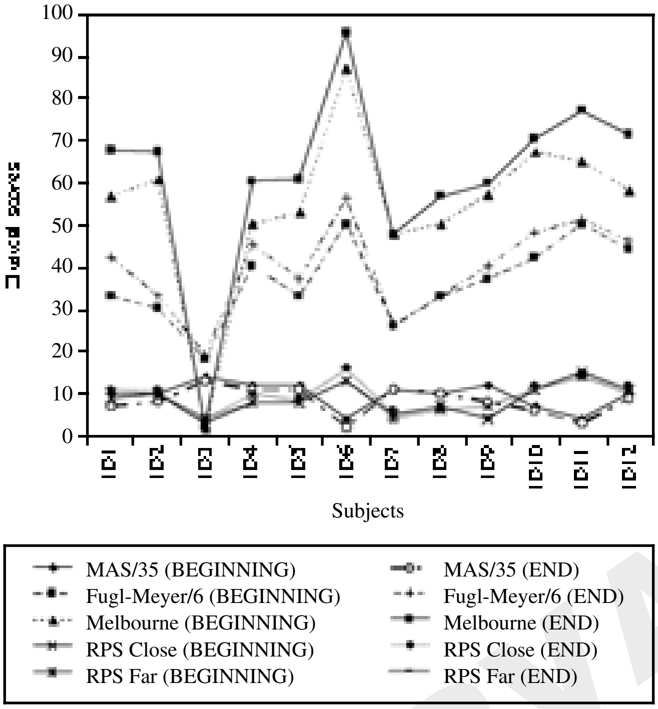

Figure 2.—Clinical scale history. Evaluation at enrolment and completion of robot-mediated therapy for each patient.

Discussion

There is a growing consensus that training might have positive impact on cerebral palsy and traumatic brain injury with the reprogramming of spared neural tissue, *i.e.,* a reorganization of the remaining cortical-subcortical networks and their descending projections.[37-40]

There is strong evidence that the organization of the brain cortex is dynamic (somato-sensory, visual, acoustic and motor) and it is directly induced by the type and intensity of the activity and context. While this appears to be true in the adult brain, there might be an even bigger window of opportunity during childhood.[41]

Our results support previous positive results on the application of robot mediated therapy to children with cerebral palsy [12] and it extends to children with TBI (traumatic brain injury). Our study demonstrated that robot mediated therapy and assisted therapy do not increase tone. On the contrary, the MAS indicated a significant reduction in tone of medium size effect. This result is consistent with the literature on intensive training in persons with chronic upper limb hemiparesis, which demonstrated no increase on spasticity and on pathologic movement patterns.[42] This result is consistent with the statistically significant gain of large effect size of Fugl-Meyer Assessment and on its components evaluating shoulder and elbow synergistic movements.

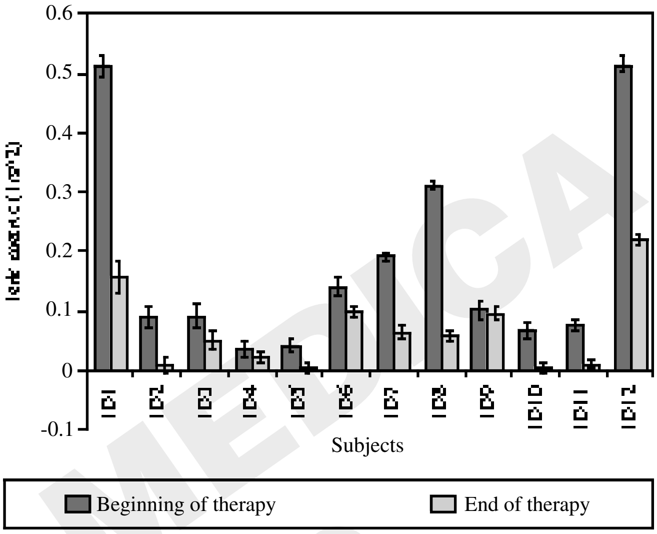

Figure 3.—Jerk metric. Results of jerk metric at the beginning and at the end of therapy. Lower value at completion of therapy indicates smoother reaching movements.

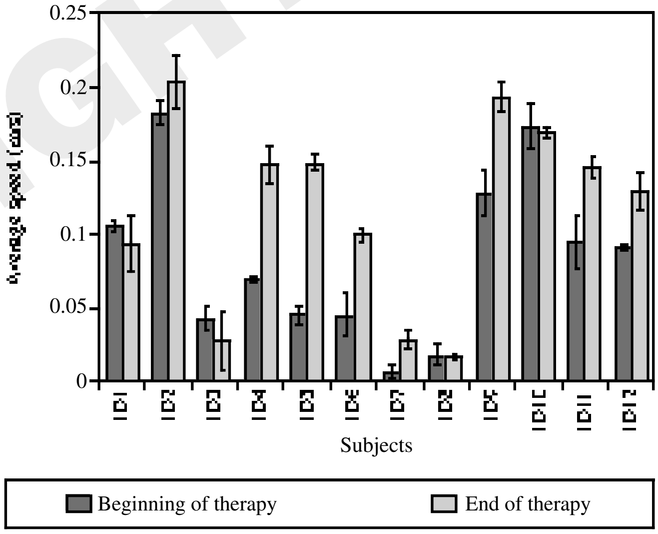

Figure 4.—Average speed. Average speed values at the end of therapy and at the beginning. The average speed seems not to have a clear trend at the beginning and at the end of therapy.

Finally, we administered the RPS to evaluate whether there was any secondary effect on postural control of the trunk. The observed improvement suggested a greater control of the head and trunk, probably due to some form of reintegration in the sensorimotor cortical system.[43]

The robot-based metrics revealed noticeable differences in trajectories, speed and jerk profiles between the first and last day of therapy. A decrease in JM indicates an increase of the smoothness of the reaching movements (Figure 3, Table II). A decrease in JM was statistically significant and occurred for all children, suggesting better shoulder-and-elbow coordination. Contrarily AS does not seem to show a clear trend over the course of therapy, resulting to be less significant for the quantification of motor performance (Figure 4, Table II). This fact may suggest JM to be more related to an improvement of motor coordination than AS which is strictly related to movement strategy while attempting the task. Movement coordination is the result of the interaction between the subject and the environment, hence between the nervous system, the body's biomechanical properties and the external environment within a particular motor task.[44, 45] A smoother trajectory with a lower jerk profile might involve a higher coordination between shoulder and elbow during the execution of planar tasks and this can be seen as a strong need in recovering natural motor ability. In fact, since during each reaching task we did not impose time constraints on patients, letting them to freely move, it is possible some of them decided to choose lower speed in order to aim the targets more accurately, while others optimized the exercise by increasing their speeds of execution. The strong trend in JM might indicate its potentiality as a useful index in recovery. Flash [46] and Rohrer [35] have employed smoothness to characterize quality of movement and recovery respectively.

Conclusions

Robot-mediated therapy in children with acquired or congenital brain injury appears to be beneficial; enhancing motivation and improving perception it incorporates the advantages of the enjoyable game-like experience. Our results demonstrated that short-term, goal-directed robotic therapy can significantly improve motor abilities of the exercised limb segments. Clinical and robot-based scores are significantly better at study completion than at enrollment, which suggests that motor recovery can be influenced by repetitive, intensive, goal-oriented exercise training without a negative impact on muscle tone or pain.

Now that RMT has demonstrated its potential, we will use this robotic technology identifying among the multiple variables which ones might have a larger impact on outcomes and influence recovery (*e.g.*, timing, intensity, and duration of therapy; type of task practiced). We expect that ultimately we will be able to develop a recovery model that will guide the rehabilitation practice of children with acquired or congenital brain injury.

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