Design of a Planar Robotic Machine for Tele-Rehabilitation of Elderly Patients

D. Accoto, L. Zollo, D. Formica, E. Guglielmelli

***Abstract*—Early Supported Discharge (ESD) aims at accelerating the patient's discharge by providing a level of rehabilitation at home similar to that guaranteed in hospitals. Information-based rehabilitation technologies expand the possibilities for several interventions to promote independent living of impaired elderly people, such as virtual reality and robot-aided tele-rehabilitation. In robot-aided tele-rehabilitation scenarios the patient uses the robot at home while the therapist is supervising the therapy from a remote location. The actual implementation of this methodology asks for the development of novel machines, which should allow the subministration of different therapies, while being easily portable and economically affordable.**

I. INTRODUCTION

Early Supported Discharge (ESD) with continued rehabilitation at home is a well-validated regimen for poststroke rehabilitation [1]. ESD aims at accelerating the patient's discharge by providing at home a level of rehabilitation similar to that allowed in hospitals [2]. Several studies on ESD have recently been published demonstrating a significant effect even in comparison with standard care based in a stroke unit [3]. Decreased length of inpatient rehabilitation stay, greater long-term injury survival rates, broader access to information technologies, and the growing role of the Internet create potential for new models of rehabilitation. In particular, information-based rehabilitation technologies expand the possibilities for numerous interventions to promote independent living of impaired elderly people, such as virtual reality and robot-aided tele-rehabilitation [4].

Robot-Aided Tele-rehabilitation is a remote rehabilitation where the patient uses the robot at home while the therapist is conducting the therapy from a remote location [5]. The enabling technologies are the Internet, which provides the communication link (data and video), and a robot, which allows the user to input motion commands and receive force feedback. Two possible configurations can be envisaged: (i) in the *unilateral* configuration only the patient needs to interact with a robot during telerehabilitation [6-8]; (ii) in the *bilateral* configuration both patient and therapist use robots.

In both case a high degree of portability is requested. This means that the robot should be light, compact and robust to be moved to and mounted at the patient's site with no or small need for specialized skills. Moreover, the robot should require few and simple assembly steps in order to shorten the length of the set-up procedure, thus allowing the therapy to start as soon as possible.

No commercial systems available at the moment fully fulfil these requirements, which should be taken into account from the early design of any robotic system for tele-rehabilitation.

This paper presents the design and development of a robot manipulator (called CBM-Motus) for the tele-rehabilitation of the upper limb. The machine is conceived to optimize the dynamic behaviour in the interaction with the patient by addressing requirements coming from the application areas of robot-aided rehabilitation and remote rehabilitation.

II. ROBOT DESIGN

Effective rehabilitation therapies require the active involvement of patients' higher cognitive functions. From a technological perspective this requirement translates in the development of robotic platforms that allow advanced interaction modalities with the human body. For this reason, but also to allow a high level of dependability, back-driveability, i.e. the ability of the robot to be moved by the patient acting on the terminal member, is often pursued.

Back-driveability can be achieved both mechatronically or mechanically. In the first case, the machine is endowed with a suitable control that drives the joints in such a way that patient's motion is properly followed. In the second case the robot is intrinsically back-driveable, even if no control is acting. A robot may be considered as mechanically back-driveable if it allows reverse motion, i.e. if energy losses due to friction in the direct motion are small enough[1]. A machine is said to be reversible if reverse motion is possible. To our purposes, we consider a robot to be back-driveable when its mechanical system is reversible and the forces to be applied to its terminal organ to achieve motion are "low enough" to be managed by the patients. From a practical standpoint, a force below 10N can be considered as "low enough". Evidently, the force at the terminal organ is the algebraic sum of inertial and frictional forces.

A mechanically back-driveable robot is generally to be preferred to the mechatronic ones, because its compliance is not affected by potential software faults, nor its response time suffers from delays related to data acquisition and processing.

On the other hand, mechanical back-driveability negatively impacts the overall cost of the robot, because it may require sophisticated hardware solutions to keep friction and apparent inertia low enough.

Manuscript received February 15, 2008.

All the authors are with the Biomedical Robotics and Biomicrosystems Lab, Università Campus Bio-Medico di Roma, Via A. del Portillo, 21 – 00128 Roma (Italy). Email: [d.accoto][l.zollo][d.formica][e.guglielmelli]@unicampus.it

Corresponding author:
Dino Accoto, tel:+39 06225419610, email: d.accoto@unicampus.it

[1] Let L be the work done by the actuators in the direct motion and F the work done by frictional forces. The kinematic efficiency is defined as $\eta = 1\text{-}F/L$. It can be demonstrated that reverse motion is possible if $\eta>0.5$.

Anyhow, both high dependability and low cost are of great importance in the scenario of tele-rehabilitation of elderly people. For this reason, we recently devised a novel reversible kinematic structure that combines a large work-space with a low friction and perceived inertia when back-driven [9].

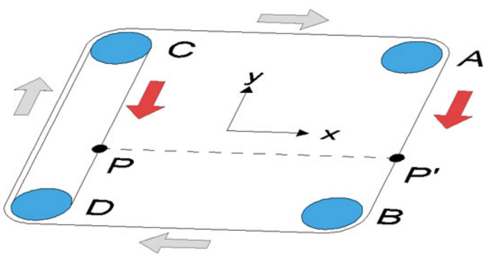

Fig. 1. A single module is comprised of 6 pulleys (two of which, in the left in the figure, are mounted on the same shafts) and 2 timing belts. Two corresponding points, P and P', move with the same speed (red arrows) and can be connected by a rigid rod.

The main requirements for the design of the robot are:

- mechanical back-driveability;
- workspace large enough to allow the administration of rehabilitation treatments (target: > 500 mm x 500 mm);
- interaction forces up to 50 N.

We decided to pursue an additional requirement related to:

- isotropic dynamic characteristics

i.e. we wish the apparent inertia not to depend from the direction of the applied force. Dynamic isotropy simplifies the dynamical model of the robot and allows the use of safer and possibly more robust control algorithms.

The kinematic structure of the CBM-motus is based on two identical modules. Each module comprises six toothed pulleys (radius: 25 mm) and two belts (timing belt XL037, 9:4 mm wide, reinforced with a glass fiber), as shown in Fig. 1. Two couples of pulleys (on the left in Fig. 1) are mounted on the same shafts. One motor per module, fixed with respect to the frame, is connected to one of the two shafts hosting two pulleys. When the motor rotates, the segments of belts AB and CD move with the same speed. Therefore, a rigid bar connected to any two points along these segments, say P and P', moves without rotation. In particular, the points are chosen so that their y coordinate is the same, and the bar is parallel to the x-axis.

The second module, identical to the first one, is rotated of 90° around the z-axis and placed with a suitable offset along the z-direction to avoid mechanical interference among parts. As the motors rotate by angles α_1, α_2 the point P of intersection of the projection the two bars in the x-y plane moves according to:

$$x = R\,\alpha_1;\; y = R\,\alpha_2$$

where R is the radius of the pulleys.

The two bars slide through a joint obtained by rigidly interlinking two prismatic joints forming a 90° angle. Such joint, visible in fig. 2, moves as the point P. The handle is mounted on the double prismatic joint and is free to rotate about its axis.

The overall kinematic structure of the CBM-Motus is shown in Fig. 2. Here, the outer prismatic joints (P1, ..., P4) correspond to the segments of the belts to which the two bars (1 and 2) are connected. The two bars slide through the double prismatic joint (A+B), to which the end-effector (E) is connected.

The two modules are actuated using DC servomotors fixed to the frame (Aerotech BM 250) with rated torque of 2 Nm and peak torque of 5 Nm. By considering the radius of the pulleys (R = 25 mm), the rated force, which the robot can be withstand, is 80 N, with a peak value of 200 N. The workspace is a square in the x-y plane (550 mm x 550 mm).

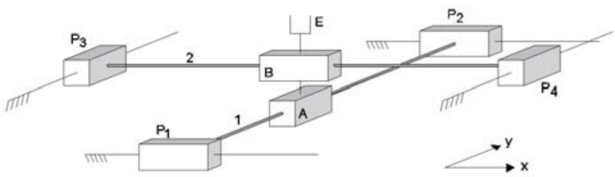

Fig. 2. Kinematic structure of the CBM-Motus. The end-effector, E, is connected to the double prismatic joint (A+B). The bar parallel to the x-axis causes the motion along the y axis, and vice-versa.

From a kinematic standpoint, the double prismatic joint allows the handle to follow the intersection point P of the sliding bars in the x-y plane. From a static standpoint the joint decouples any interaction force, applied to the end-effector, into two components, Fx and Fy, respectively parallel to the x and y axis. This decomposition assures that, for any applied force, belts are purely stretched (no bending). Therefore, even if the sliding parts are connected to belts, a great degree of stiffness is easily achieved, with a significant reduction of moving masses (and therefore inertia) if compared to the conventional solution where the bars are supported at one end and moved by a belt at the other end. The use of timing belts reinforced with glass fibers improves the tensile stiffness of the compliant parts, with advantages for the overall rigidity of the robot.

This feature, together with the low mass of the belts, assures a high resonance frequency, which is necessary to avoid vibrations or any other spurious mechanical stimuli. Moreover, the pretension of the belts can be adjusted during assembly by acting on pretension screws. In this way, the resonance frequency can be manually tuned.

The stiffness along the z-axis is achieved by a supporting ball bearing located beneath the double prismatic joint. The ball bearing compensates the bar own weight, as well as the patient's arm weight and any z-component of the interaction force.

Fig. 3 shows an overview of the structural parts of the robot (motors included). The moving mass along each direction is less than 2.6 kg. An overview of the assembled system is given in fig. 4. The outer dimensions of the robot are 830 x 820 x 110 mm. The total mass (frame and motors included) is about 30 kg.

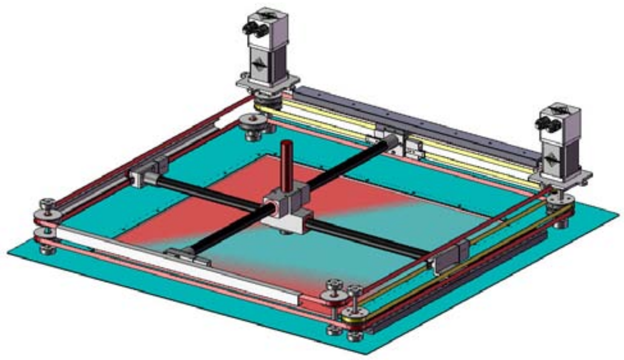

Fig. 3. Overview of the structural parts of the CBM-Motus. The system of pulleys and belts are visible, as well as the moving bars.

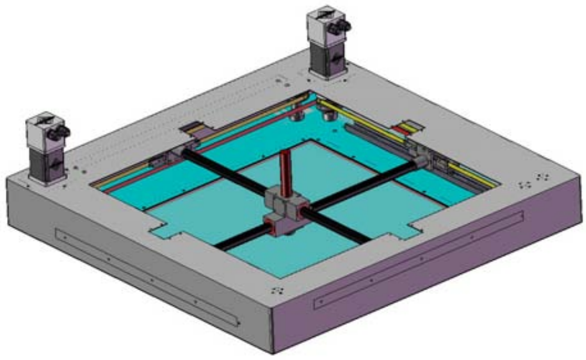

Fig. 4. Overview of the assembled system.

III. Kinematic and Dynamic analysis

The CBM-Motus robot can be regarded as a Cartesian manipulator with two linear joints d_1 and d_2. The robot forward kinematics (Fig. 2) is very easy:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}$$

The Jacobian matrix is:

$$J = \begin{bmatrix} z_0 & z_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The Lagrangian formulation is used to derive the following robot dynamic model:

$$B(q)\ddot{q} + c(q,\dot{q}) + F_v\dot{q} = \tau,$$

being

$$B = \begin{bmatrix} m_{l1} + I_{m1}/R^2 & 0 \\ 0 & m_{l2} + I_{m2}/R^2 \end{bmatrix}$$

the inertia matrix (independent on the robot configuration), $C(q,\dot{q}) = [0 \quad 0]^T$ the vector of centrifugal and Coriolis torques, and $F_v\dot{q}$ the viscous friction torque with f_{vii}= 1.53 Ns. In the inertia matrix B the coefficients m_{l1} and m_{l2} (with $m_{l1} = m_{l2}$) stand for the translating masses (bars, belts and handle) while $I_{m1} = I_{m2}$ are the moments of inertia due to the two motors and the twelve pulleys (R is the pulleys radius).

The study of the CBM-Motus dynamic properties has been carried out through the estimation of the robot inertial and acceleration capabilities in the workspace and their spatial representation through ellipsoids.
The approach is resumed from [10-12] and consists of calculating and analyzing the generalized inertia tensor (Λ_v) and the acceleration matrix (E_v) and representing them graphically using the inertia and acceleration ellipsoids.
In particular, the inertial features of the robot can be described through:

1. $\|\Lambda_v\|$which describes the magnitude of inertial quantities (the robot design tends to minimize them);
2. k (Λ_v) (where $k(\cdot)$ is the matrix condition number), which quantifies the level of isotropy of the inertial properties. In particular, k (Λ_v) = 1 means perfect isotropy.

In the same way robot acceleration capabilities can be evaluated by means of:

1. $\|E_v\|$ which measures the magnitude of acceleration capability (acceleration is maximized when $\|E_v\|$ is maximized).
2. k (E_v) which measures the isotropy of acceleration capabilities, as for the inertia.

Further details on the mathematical formulation of this method can be found in [10-12,13].
Figure 6 shows the inertia ellipses for the CBM-Motus, in the nine Cartesian positions (P1,.., P9) that the robot reaches while performing the rehabilitation clock task (shown in Fig. 5), as in [14-16]. Moreover, Tables I reports the values of the CBM-Motus inertial parameters in the nine points. The inertia matrix for the CBM-Motus is independent from the robot configuration. Thus, the mass perceived at the end effector has the same value everywhere in the workspace and is 2.59 Kg. Also, the CBM-Motus is isotropic (k (Λ_{vMotus}) = 1).

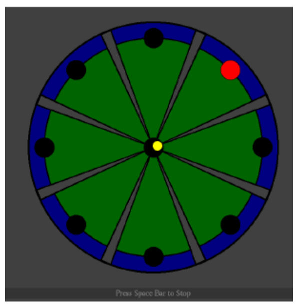

Fig. 5. Graphical interface for the rehabilitation clock exercise.

Similarly to the inertia analysis, Fig. 7 shows the torque ellipses in the nine positions of the clock task, while Table II reports the acceleration parameters for measuring the magnitude of the acceleration properties and the level of isotropy of the CBM-Motus. As expected, the robot is isotropic (k (E_{vMotus}) = 1) with a constant value of $\|E_{vMotus}\|$ = 0.52 s^2. The constant maximum acceleration is 2.7 m/s^2. These values satisfy the condition of tangency with the square of torque bounds, being 5 Nm the bound for the CBM-Motus.

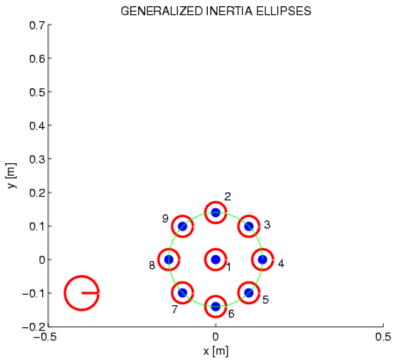

Fig. 6. Inertia ellipses for the CBM-Motus robot during the rehabilitation clock exercise.

	P1	P2	P3	P4	P5	P6	P7	P8	P9
$k(\Lambda_{vMotus})$	1	1	1	1	1	1	1	1	1
$\|\Lambda_{vMotus}\|$	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59

Table I. Inertia parameters for the CBM-Motus robot during the clock exercise.

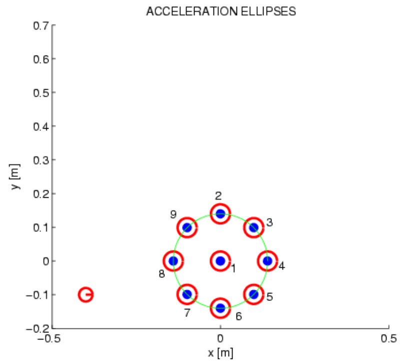

Fig. 7. Torque ellipses due to acceleration for the CBM-Motus robot during the rehabilitation clock exercise.

	P1	P2	P3	P4	P5	P6	P7	P8	P9
$k(E_{vMotus})$	1	1	1	1	1	1	1	1	1
$\|E_{vMotus}\|$	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52

Table II. Acceleration parameters for the Mit-Motus robot during the clock exercise.

IV. Use in Tele-rehabilitation Scenario

The design of the CBM-Motus addresses specific requirements related to the tele-rehabilitation of elderly, typically post-stroke, patients. In this scenario a high degree of portability and robustness are requested. For this reason the robot has been designed to be light, compact and robust to be moved to and easily mounted at the patient's site.

Also, the low cost is one of the requirements that the machine tries to address through the simplicity of its mechanical system.

Moreover, the machine has been conceived to optimize the dynamic behaviour in the interaction with the patient by addressing requirements of high levels of safety and dependability.

The robotic machine is currently being developed for remote upper limb motor therapy [13,17,18] in the unilateral configuration, taking care of in-depth studying issues related to communication on intermittent basis or in real-time (that are critical for ensuring safety in the interaction). In order to facilitate patients' access to the use of the machine, a user interface will be developed with the following key elements: *evaluation tests* that assess user motion capabilities and periodically measure rehabilitation progress; *therapy games* that consist of a library of games for practicing sensory-motor therapy; *progress data* that provide the user with quantitative feedback of rehabilitation progress; *therapist page* that allows the therapist to interact with the patient by designing and adjusting rehabilitation programs, to supervise the therapy and intervene on the system when needed; *rehabilitation programs*, to monitor the patient and the execution of the rehabilitative exercise, to assess the rehabilitation progress.

A gradual increase of interactive control and cooperation with the therapist in remote location, up to the bilateral configuration is finally envisaged.

References

[1] Thorsén AM et al., Journal of Stroke and Cerebrovascular Diseases, 2006, 15(4): 139-143.

[2] Langhorne P et al., J Rehabil Med, 2007, 39: 103-108.

[3] Larsen T et al., *Intl J of Technology Assessment in Health Care*, 2006, 22(3):313-320.

[4] Carignan CR et al., *Journal of Rehabilitation Research & Development*, 2006, 43(5):695-710.

[5] Krebs HI et al., IEEE Trans Rehabil Eng. 1998, 6(1):75–87.

[6] Jadvah C et al., 26th Annual International Conference IEEE Engineering in Medicine and Biology Society (EMBS, 2004, 3297-3300.

[7] Reinkensmeyer DJ et al., *IEEE Trans Neural Syst Rehabil Eng*, 2002, 10(2):102-108.

[8] Popescu VG et al., *IEEE Trans Inf Technol Biomed*, 2000, 4(1):45-51.

[9] Accoto D et al., patent no. RM2008A000242 filed May 8, 2008.

[10] Asada H, *IEEE International Conference on Robotics*, 1984, 94-102.

[11] Khatib O, *International Journal of Robotics Research*, 1995, 14: 19-36.

[12] Khatib O et al., *IEEE International Conference on Robotics and Automation,* 1996, 2283–2289.

[13] Zollo L et al., *ICRA 2008 – International Conference on Robotics and Automation*, 2008, in press.

[14] Fasoli S E et al., *Arch Phys Med Rehabil*, 2004, 85: 1106–1111.

[15] Krebs H I et al., *IEEE Transactions on Rehabilitation Engineering*, 1998, 6: 75-87.

[16] Krebs H I et al., *IEEE Trans Neural Syst Rehabil Eng*, 2007 15: 327-335.

[17] Zollo L et al., in *Rehabilitation Robotics*, Advanced Robotic Systems Eds., 2007, 619-638.

[18] Formica D et al., *ASME Journal of Dynamic Systems, Measurement, and Control*, 2006, 128:152-158.