Design and Control of a Robot-Arm Actuated by Pneumatic Artificial Muscles for Post-stroke Rehabilitation

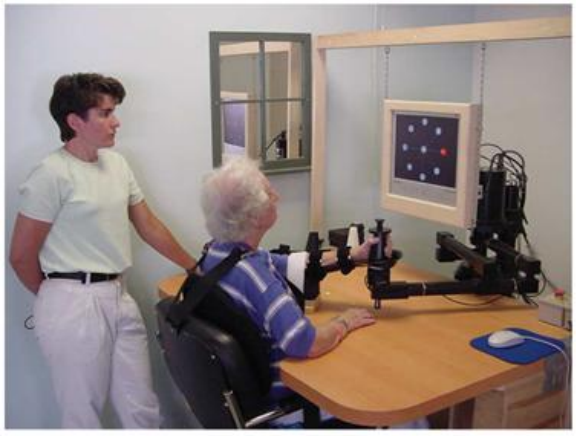
Bertrand TONDU,[1] Mathias ATTIMS[1] and Emmeline MONTANE[2]
[1]LAAS-CNRS and INSA, University of Toulouse, [2] Toulouse-Purpan University Hospital Center (CHU), University of Toulouse, France

ABSTRACT - Robots play a significant role in post-stroke rehabilitation thanks to the possibility they offer to perform simple, effective and fun repetitive exercises. They are mainly driven by electric motors combined with position or force control in the robot's task space, but with high stiffness of the movements proposed to the patient. The use of an actuation mode by artificial muscles opens the way to biomimetic flexibility of the robot's movements, in interaction with the patient. We present in the article the realization of a prototype robot with two degrees of freedom, for the rehabilitation of the upper limb, driven by pneumatic artificial muscles.

Keywords—Post-stroke rehabilitation, artificial muscles, passive and active mode in kinesiology.

1. INTRODUCTION

Stroke is the leading cause of disability in adults in developed countries [1], and the leading cause of long-term disability in adults in Europe [2]. Post-stroke management is particularly costly for society [3] because of increasingly effective medical interventions and the implementation of re-education facilities over a long period. Moreover, the lengthening of the life span will lead developed societies to face higher prevalence, and therefore an increase in associated costs. If the patient survives a stroke, he/she has cognitive and motor aftereffects that a gradual and constant reeducation can nevertheless significantly mitigate, potentially reaching full functional recovery. Motor rehabilitation is particularly important to restore the patient's autonomy; it generally concerns both the lower limbs and the upper limbs - with particular attention to the so-called paretic side, i.e. contra-lateral to the injured cerebral hemisphere - to recover gestures of daily life. In this medical context, robotics has already proven its advantage for an adapted and intensive training without requiring a continuous presence of the therapist close to every individual patient. If we limit ourselves to the upper-limb, as considered in this article, the *Armeo Power* [4] and the *MIT-MANUS* [5], shown in Fig. 1.a, are examples of such post-stroke rehabilitation robots. More recently, the *REAplan* developed by the Belgian company *Axinesis* (www.axinesis.com) is a two degrees of freedom Cartesian robot proposing rehabilitation exercises according to the principle of "serious games", as illustrated in Fig. 1.b. By means of a Cartesian force located at the robot end-effector, three functioning modes are distinguished: an "active mode" where the patient can move freely in the working space of the robot with a zero Cartesian force imposed at his/her hand, a "passive mode" imposing to the patient to follow prescribed trajectories and a "active-assisted mode" where free movements of the patient towards a specified goal, or along a prescribed trajectory, are assisted by position and force control. As recent studies have shown, rhythmic upper limb movement training improves motor skills in both rhythmic and discrete movements after stroke [6], [7].



(a)

(b)

Fig. 1. Examples of upper limb rehabilitation robots working in a plane: (a) *MIT-Manus* (from [5]), (b) *REA-plan* installed in a French rehabilitation service (from the web site of *Ouest France*, October 12, 2018).

All these rehabilitation robots are purely electric. The originality of our proposal lies in replacing electric motors with artificial pneumatic muscles, thus combining pneumatic energy and electrical technology with the hope to get new possibilities of soft movements for the patient by comparison with a classical electric actuation, and new facilities in rehabilitation. As illustrated in Fig. 2, the objective of using robots for rehabilitation is to take advantage of simple exercises that promote, through their repetition, the recovery of healthy muscular neural control profiles that, according to H. Hirai et al. [8], can be characterized by the sum of agonist and antagonist neural activations ("AA sum") and their ratio ("AA ratio"). In our opinion, the use of an actuator with antagonistic artificial muscles could facilitate the recovery of these "AA sum" and "AA ratio" profiles.

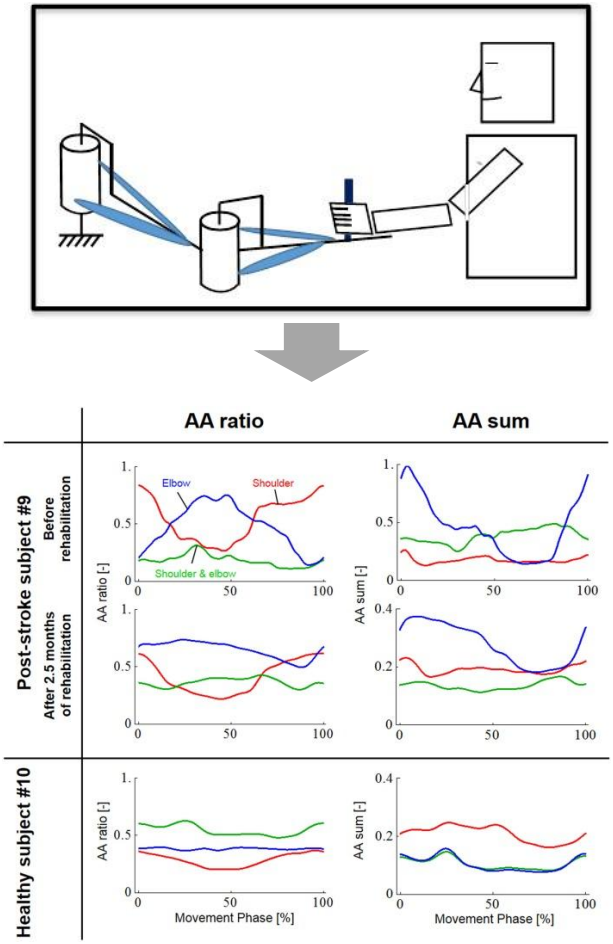
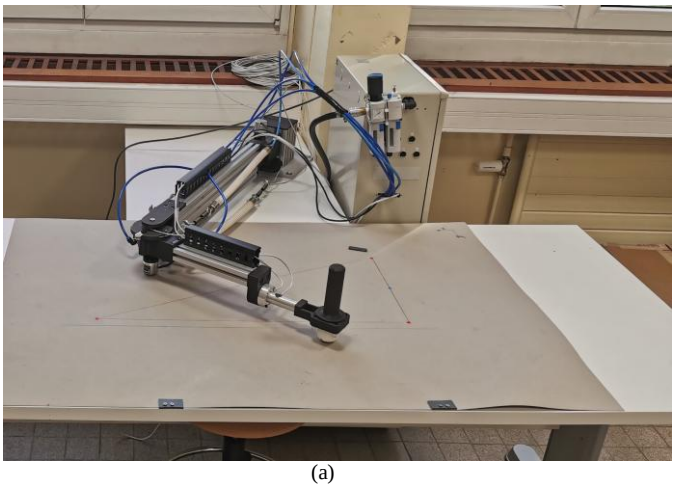


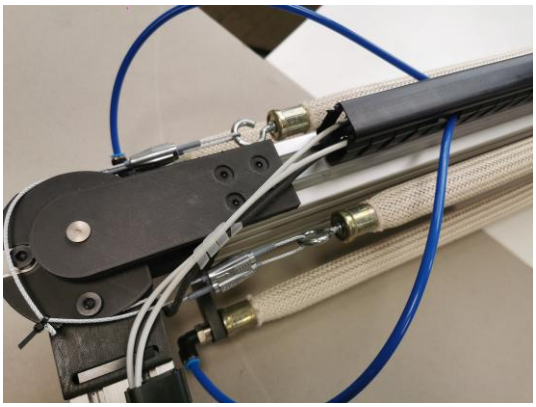
Fig. 2. Principle of using a rehabilitation robot actuated by artificial muscles for the recovery of neural activation control profiles of agonist and antagonist muscles - see text (the lower part of the figure is reproduced from H. Hirai et al. [8]).

2. General structure of the robot

The actual version of our prototype is shown in Fig. 3. Its mechanical structure, developed in collaboration with the *Louvain Bionics* (*Université Catholique de Louvain-la-Neuve*, Belgium) [9] is both inspired by the *MIT-Manus*, with its 2 degrees of freedom SCARA-like structure, and by the *REA-plan* with its three functioning modes: passive, active, and active-assisted. Let us recall that, in physiotherapy, active rehabilitation is an all-encompassing term used to describe a recovery-based program where the patient plays an "active" role in the proposed exercise, with eventual assistance. By opposition, passive rehabilitation is understood as any exercise where the patient is guided by the therapist. When a robot is used for rehabilitation, the patient is never alone, accompanied by a caregiver, but it is the robot that plays the role of the therapist, to whom its terminology is applied.



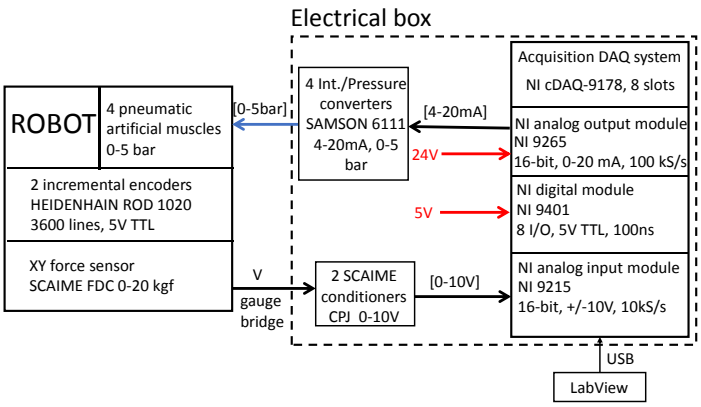
(a)



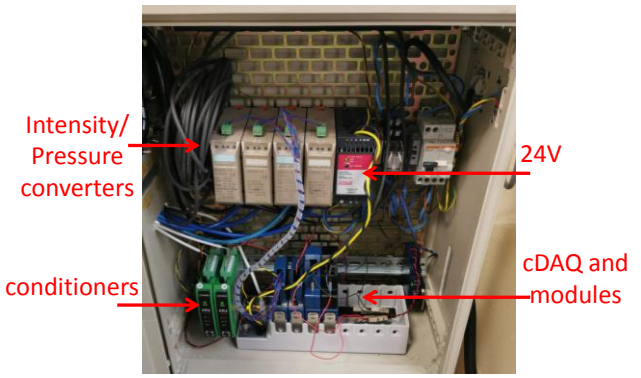
(b)

Fig. 3. Prototype of a 2 degrees of freedom rehabilitation robot-arm actuated by antagonist pneumatic artificial muscles, installed at the INSA of Toulouse: (a) General view, (b) Closed-up of the hand-made McKibben pneumatic artificial muscle actuators.

The robot is a SCARA type structure whose movements are limited in the plane with a first degree of freedom for the shoulder and a second degree of freedom for the elbow. Each degree of freedom is actuated by the same artificial muscles manufactured in the laboratory whose initial length, excluding tips, is equal to about 48 cm with a maximum contraction rate of approximately 30% under 5 bar. The choice of artificial muscles was made to allow movements in a square of 40 cm by 40 cm with a force of up to 20 kgf throughout this area. The robot controller was developed in *LabView* with a real-time *National Instrument*-architecture based on a cDAQ-system, as synthesized in Fig. 4a. The resulting robot controller is shown in Fig. 4b: the four artificial muscles are supplied with pressure, in a [0-5bar] range via intensity/pressure converters; joint position is measured by incremental encoders and the Cartesian force at the end-effector of the robot by a XY-force sensor.



(a)



(b)

Fig. 4. General structure of the robot controller (a) and photography of its physical realization (b).

3. Mimicking the variable stiffness ability of human body by antagonistic artificial muscles

In a seminal paper, N. Hogan [10] proposes a very simple model of the skeletal muscle active contraction force that we can write in the following form:

$$F(\varepsilon) = uF_{max}\left(1 - \frac{\varepsilon}{\varepsilon_{max}}\right), 0 \le \varepsilon \le \varepsilon_{max} \; and \; 0 \le u \le 1 \tag{1}$$

where F is the static muscle force, ε is the muscle contraction ratio defined as the ratio $(l_0–l)/l_0$ with l_0 the initial muscle length and l the current muscle length. According to this model, the force F is maximal – of F_{max} value – when $\varepsilon = 0$ and equal to zero when $\varepsilon = \varepsilon_{max}$. The u-variable represents the normalized neural activation. The biceps-triceps system realizes a typical antagonist actuator modelled by two identical equivalent muscles linked by a pulley of radius R, as illustrated in Fig. 5. The resulting torque T is given by:

$$T = R[F_a(\varepsilon_a) - F_t(\varepsilon_t)] \tag{2}$$

with:

$$\begin{cases} F_a(\varepsilon_a) = u_a F_{max}\left(1 - \dfrac{\varepsilon_a}{\varepsilon_{max}}\right) \text{ and } \varepsilon_a = \varepsilon_0 + R\theta/l_0 \\ F_t(\varepsilon_t) = u_t F_{max}\left(1 - \dfrac{\varepsilon_t}{\varepsilon_{max}}\right) \text{ and } \varepsilon_t = \varepsilon_0 - R\theta/l_0 \end{cases}$$

where ε_0 is typically equal to $\varepsilon_{max}/2$ generated by u_0 in the initial state (Fig. 5a).

Such actuator is stable in open-loop i.e. a stable equilibrium position can be realized by a choice of u_a and u_t-variables. Moreover, if we assume the independence of u_a and u_t, a MIMO (Multiple Input-Multiple Output) actuator results making possible to control both θ-position and S-stiffness – defined as the ratio $(\delta T/\delta\theta)$ – whose following expressions can be deduced from Equs. (1) and (2):

$$\begin{cases} \theta = \dfrac{l_0(\varepsilon_{max} - \varepsilon_0)(u_a - u_t)}{R(u_a + u_t)} \\ S = \dfrac{R^2 F_{max}}{l_0 \varepsilon_{max}}(u_a + u_t) \end{cases} \tag{3}$$

As a consequence, joint stiffness appears to be proportional to the sum $(u_a + u_t)$ while, for a constant stiffness, joint position is proportional to the difference $(u_a – u_t)$.

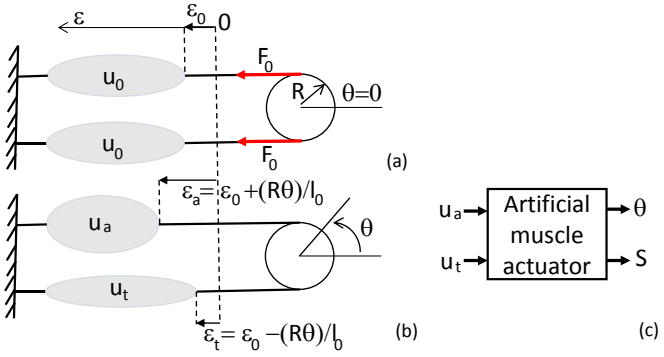


Fig. 5. Antagonist artificial muscle actuator considered as a MIMO actuator with two inputs: u_a and u_t and two outputs: θ and S – see text.

The so-called pneumatic McKibben artificial muscle is, among the large family of artificial muscles, one of them whose static force-contraction characteristics is the closest with model of Equ. (1) [11], [12]. In a more recent paper, we developed a static model of the actuator made of two identical McKibben muscle with a focus on the industrial version of the McKibben muscle, named air muscle and commercialized by the German Festo company (https://www.festo.com) [13]: by analogy with Equ. (3), joint stiffness appears to be controllable by the sum of agonist and antagonist pressures, respectively noted P_a and P_t while joint position is controlled by their difference. If we call P_0 the initial pressure, corresponding to the initial u_0-parameter, the control pressure in each artificial muscle is realized by a $+\Delta P$ pressure variation in the agonist muscle and $-\Delta P$ in the antagonist muscle according to the relationships:

$$\begin{cases} P_a = P_0 + \Delta P \\ P_t = P_0 - \Delta P \end{cases} \Rightarrow \begin{cases} \Delta P = \left(\frac{1}{2}\right)(P_a - P_t) \\ P_0 = \left(\frac{1}{2}\right)(P_a + P_t) \end{cases} \tag{4}$$

As a consequence, by making P_0 variable, we so make possible the modulation of stiffness of each joint. However, as will be discussed in the conclusion, Hogan's muscle model is a model of the active part of the muscle, i.e., a model of the muscle considered as a pure "active spring," and McKibben's artificial muscle is in perfect agreement with this approach. Therefore, the pressure P_0 cannot be zero since the actuator "tendons" are

assumed to be inextensible. Moreover, it is important to note that the optimal choice for ε_0 and P_0 is $\varepsilon_{max}/2$ and $P_{max}/2$, respectively, with, consequently, a range for ΔP equal to [0, $P_{max}/2$]: when $\Delta P=P_{max}/2$, the agonist muscle is inflated to P_{max} with $\varepsilon_a=\varepsilon_{max}$, while the antagonist muscle has zero pressure with $\varepsilon_t=0$. If P_0 is set to a pressure lower than $P_{max}/2$, the pressure in the agonist muscle cannot exceed $2P_0$ instead of P_{max}. A value greater than $P_{max}/2$ for P_0 implies a minimum value in the antagonist muscle equal to ($2P_0 - P_{max}$), with, in both cases, a corresponding limitation of the joint range of motion. In other words, the joint range of motion depends on the joint stiffness. This is a limitation of our actuator in this MIMO control approach.

4. TOWARDS SOFT MOVEMENTS FOR REHABILITATION INCLUDING STIFFNESS MODULATION

The actual version of the LabView controller of our robot is based on the opposition between passive and active modes, as considered for the use of the REAplan. The user interface is shown in Fig. 6: it gives the possibility to switch from a mode to another mode, including a manual mode defined as an open-loop control of the artificial muscles i.e. a direct control of pressures P_0 and ΔP for each actuator. Particular attention has been paid to facilitating the management of curves on the screen in order to have real-time access to joint trajectories such as Cartesian, pressure commands and joint torques, such as Cartesian forces.

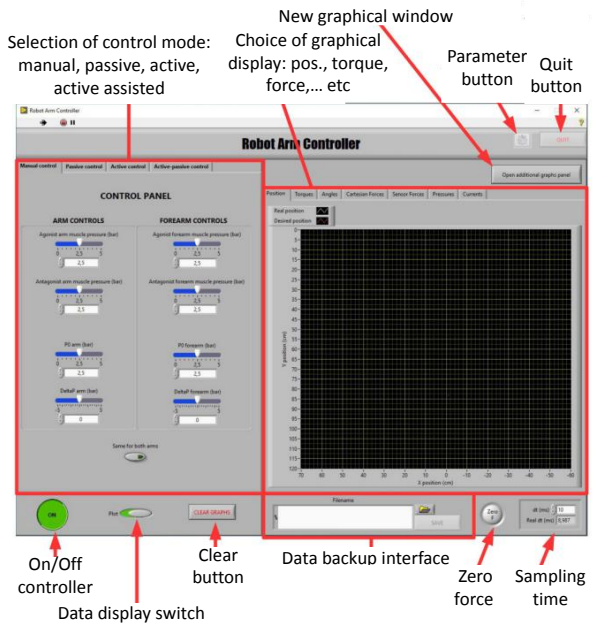


Fig. 6. User interface – see text.

The passive mode was programmed in the form of plane trajectories from a starting point to a final point through imposed via points. The movement between each pair of points is specified according to a trapezoidal velocity profile whose cruising speed can vary until 0.5 m/s which is in accordance with the REA-plan manual specifying a cruising speed in a [2-10 cm/s]-range. Pending the development of a game graphical interface, as shown in Fig. 1b, a typical exercice is proposed to follow a triangle drawn on the robot table. It is important to note that, in this approach, the robot is used as a teach-pendent, i.e. the sequence of points to be learned to specify the task to be performed in this passive mode has been previously recorded by the robot controller after the operator has moved the robot while keeping it in zero-force active mode (see later). This passive mode is in fact programmed according to the functional diagram shown in Fig. 7: no actuator or robot model is used as an anticipation term; only fixed PID gains are considered for each joint. As defined in the previous paragraph, the pressure P_0 can be modified in real time in order to modulate the joint stiffness during the exercise.

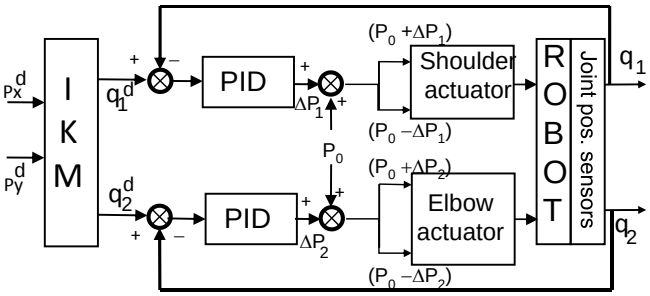
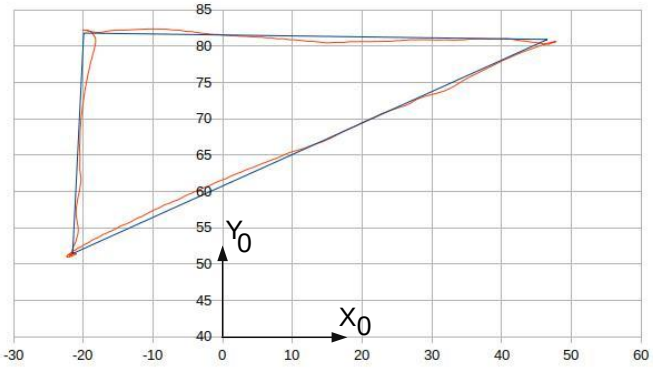
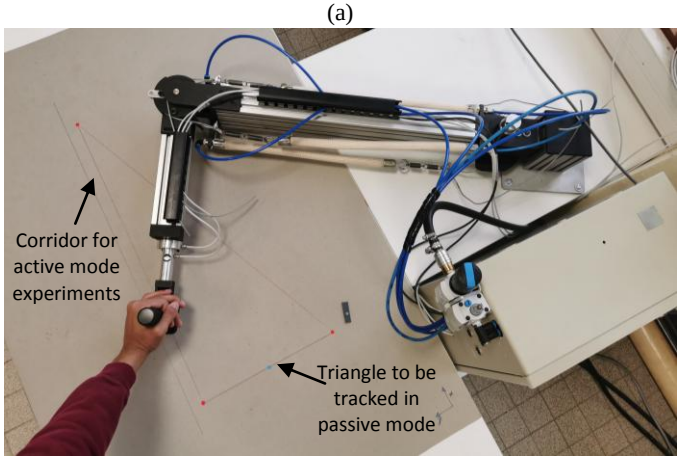


Fig. 7. Block scheme for the passive mode interpreted as a Cartesian trajectory control mode (*IKM* is for inverse kinematic model, and ΔP_1, ΔP_2 are respectively for the control of the shoulder actuator and the elbow actuator.

How we tested the passive mode is illustrated in Fig. 8.



(a)



(b)

Fig. 8. Example of passive mode performed with the robot: (a) Triangle (in red) to be tracked performed by the robot alone (in black) – distances are in cm, (b) The operator guided by the robot for following the prescribed triangle drawn on the table – see text.

In Fig. 8a we show the comparison between the prescribed path (in red) and that carried out by the robot alone (in black): an average tracking error of about 2mm is observed. Furthermore, during the passive mode test, illustrated in Fig. 8b, no instability was observed and the robot appeared powerful enough to guide the operator's hand and even to pull it. When the latter deviates from the imposed trajectory, it is gently brought back onto the trajectory by the natural stiffness of the robot's actuators combined with the stiffness of the closed-loop PID regulator, adjusted so as not to stifle the natural stiffness of the actuator.

The active mode requires the use of the end-effector 2D-Cartesian force for making possible to move the robot end-effector with zero force or to move it against a constant prescribed force. Fig. 9 gives the corresponding block-scheme. The active mode with resistance was tested along an horizontal corridor drawn on the robot table (see Fig. 8.b) with a force varying between 1 and 5kgf.

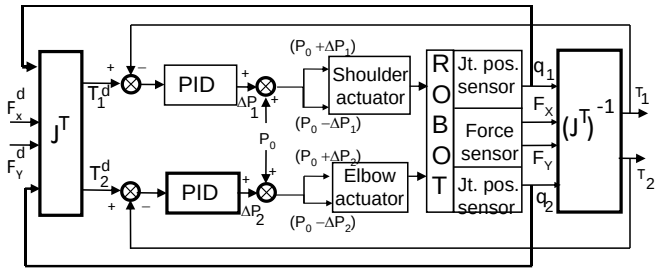


Fig. 9. Block-scheme for the active mode interpreted as a Cartesian force control mode (***J*** is for the robot Jacobian).

According to the medical team at the Purpan University Hospital in Toulouse, where the REAplan is used daily, most of the exercises performed with it favor the active-assisted mode. The originality of this active-assisted mode lies in the combination of force control associated with a position constraint, as illustrated in Figure 10.

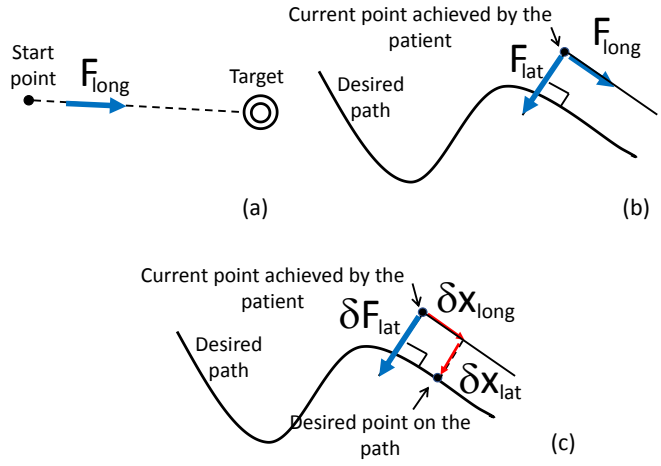


Fig. 10. Active-assisted mode principle: (a) Case of a movement prescribed towards a target, (b) Case of a trajectory to follow – both inspired by the user manual of the REAplan ([14], page 60), (c) Interpretation of the active-assisted mode as a hybrid position-force control mode – see text.

In the case of a simple pointing task (Fig. 10a), a force control is programmed in the direction of the line joining the start point with the target point, and its module can be modulated with respect both the distance to the target and the patient's resistance force. In the case of a trajectory to be tracked (Fig. 10b), the assistance is programmed as a return force towards the desired trajectory with its two components : a longitudinal one along the tangential direction of the path and a lateral one orthogonal to the path. In pratice, always according to the user manual of the REAplan, the active-assisted mode is defined by two parameters selected by the operator: a cruising velocity on the path, from 2cm/s and 10cm/s and a "maximum force exerted by the robot" ([14], page 46). We checked by ourselves without grabbing the end-effector, the robot moves by itself along the prescribed path, like in the passive mode. We are thus led to interpret the active-assisted mode as a hybrid position-force control mode, as we attempted to illustrate it in Fig. 10c: position control is limited to the tangential direction of the path – i.e. δx_{long} is the position error to be considered – while the force control is limited to the orthogonal direction – i.e. δF_{lat} is the force error to be considered. As a consequence, a lateral stiffness can be defined according to the simple formula:

$$S_{lat} = \delta F_{lat} / \delta x_{lat} \, . \qquad (5)$$

In the case of the REAplan with its very stiff electric motors, this deviation is very weak and the value of S_{lat} very high. In the case of our prototype with artificial muscles, we checked this possibility of programming the active-assisted mode as a hybrid position-force control mode, and we checked the ability of the robot to be controlled in force orthogonally to the prescribed trajectory while allowing the patient the possibility of deviating from this trajectory. As a consequence, the active-assisted mode programmed as a hybrid position-force control mode leads to a variable stiffness control orthogonally to a prescribed trajectory.

5. Conclusion and Future Work

Through a series of preliminary experiments, we were able to demonstrate the feasibility of operating a physical rehabilitation robot arm with pneumatic artificial muscles. Compared to the REAplan, which served as a reference in this study, we obtain comparable performances in speed since our robot can move its terminal organ up to 1 m/s in its workspace, but lower in force: in our active mode, the resistance or support force is limited to a few kgf while the REAplan can impose a force up to 17.5 kgf in active-assisted mode. This last limitation is a consequence of the fact that our robot, by analogy with the animal musculoskeletal system, adopts a direct drive, while a robot with electric actuators generally has speed reducers that amplify the motor torque. The biomimetic consequence in our case is this natural compliance which is at the heart of our project and which we were able to verify in the three programming modes: passive, active and active-assisted.

However, our objective goes beyond this simple natural compliance to achieve a true modulation of stiffness during the proposed exercises, based on the independence of the commands in the agonist and antagonist muscles. Since joint stiffness is directly associated with the sum of the control pressures of the agonist and antagonist muscles, respectively equal to $P_0+\Delta P$ and $P_0-\Delta P$, we made the P_0 parameter adjustable; the results obtained remain disappointing from the point of view of the feeling of the variation in stiffness at the level of the robot's end organ. In a previous work carried out at

Louvain Bionics on a similar robotic structure powered by industrial Festo pneumatic muscles, we showed that the ability of an actuator, with two identical DMSP-20-400 air muscles, to modulate its joint stiffness was limited to about 2.5 [15], while the variation of elbow joint stiffness in a certain variety of task can be estimated to be close to 8 [16]. The use of hand-made McKibben muscles with thinner inner rubber tubes than those used by the industrial *Festo* slightly extended this range, but not significantly. It is clear, in fact, that the actuator composed of two antagonistic McKibben muscles controlled in a typical pressure range [0-5 bar] has a limited ability to modulate its stiffness in comparison, for example, with some VSA actuators: in their study, M. Baggeta *et al.* indeed report a stiffness varying between 2417 Nmm/rad to 15830 Nmm/rad [17] i.e. in ratio equal to about 6.5. This limitation of the McKibben pneumatic artificial muscle actuator – as indeed for other types of pneumatic artificial muscles is due, in our opinion, to the non-extensibility of the artificial muscle which has, as a practical consequence, to have to define the zero position of the actuator by a non-zero pressure P_0 generating, for an initial contraction rate ε_0, the force F_0 allowing the initial tension of the actuator cables. The optimal choice of parameters (P_0, ε_0) to take advantage of the entire range of variation of the angular position allowed by the pair of antagonistic muscles is equal to ($P_{max}/2$, $\varepsilon_{max}/2$) with, as a consequence, to limit the range of variation of P_0 to modulate the stiffness.

To overcome this difficulty, we plan to develop a new version of McKibben's pneumatic artificial muscle that would include an essential biomimetic element to facilitate this stiffness modulation, namely passive tension. In the case of our musculoskeletal system, this is responsible for tensioning the natural muscle between its insertion points in the absence of any nervous command. For the artificial muscle, this would involve introducing a "passive spring" type element in addition to the "active spring" type motor element as we attempt to illustrate in Fig. 11: in contrast to the current structure (a), the presence of passive tension would make a zero-position at zero pressure possible (b) with a $F_{passive}$ tension instead of F_0.

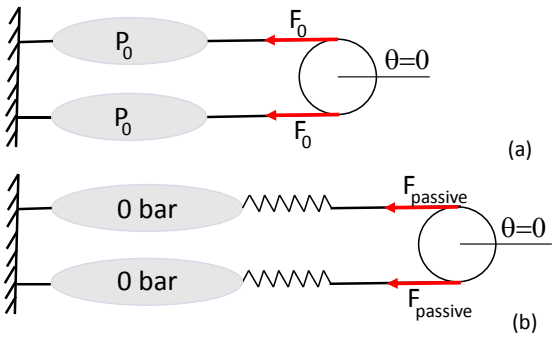


Fig. 11. Draft of a revised version of McKibben's pneumatic muscle considering an additional element of "passive tension" allowing the extension of the artificial muscle at rest (b) in contrast to its non-extensible version (a) – see text.

How can we create this passive tension without compromising the compactness of the McKibben muscle and its ease of implementation within the antagonist muscle actuator? This is the challenge of our future work.

6. Aknowledgement

We warmly thank the French Occitanie region for the support it has provided to this project as part of the "Human-Centered Robotics" Key Challenge (Défi-clé Robotique).

7. References

[1] W. Rosamond, K. Flegal, K. Furie et al. "Heart disease and stroke statistics 2008 update: A report from the American Heart Association Statistics Committee and Stroke Statistics Subcommittee", *Circulation*, Vol. 11, N°4, 2008, pp. e25-e146.

[2] T. Trueslen, B. Piechowski-Jozwiak, R. Bonita et al., "Stroke incidence and prevalence in Europe: A review of available data", *European Journal of Neurology*, Vol. 13, N° 6, 2006, pp. 581-598.

[3] L. Brewer, F. Horgan, A. Hickey et D. Williams, "Stroke rehabilitation: Recent advances and future therapies", *QJM: monthly journal of the Association of Physicians*, 2012, Vol. 106, N°1, pp. 11-25.

[4] Armeo Power: robotic exoskeleton for upper extremity rehabilitation, https://www.hocoma.com.

[5] J. Hidler, D. Nichols, M. Pellicio and K. Brady, "Advances in the Understanding and Treatment of Stroke Impairment Using Robotic Devices", *Topics in Stroke Rehabilitation*, Vol. 12, N°2, 2005, pp. 22-35.

[6] P. Leconte and R. Ronsse, "Performance–based robotic assistance during rhythmic arm exercises", *Journal of NeuroEngineering and Rehabilitation*, Vol. 13, N°82, 2016 (16 pages).

[7] P. Leconte, G. Stoquart, T. Lejeune and R. Ronsse, "Rythmic upper-limb movement training enhances motor skills of both rhythmic and discrete movements after stoke: A longitudinal study", *International Journal of Rehabilitation Research*, Vol. 1, N°1, 2018 (30 pages).

[8] H. Hirai, F. Miyazaki, H. Naritomi, K. Koba, T. Oku, K. Uno, M. Uemura, T. Nishi, M. Kagayama and H.I. Krebs, "On the origin of muscle synergies: invariant balance in the co-activation of agonist and antagonist muscle pairs", *Frontiers in Bioengineering and biotechnology*, Nov. 2015 (16 pages).

[9] J. Guiaux Brinon, R. Ronsse, L. Marsano da Costa Nunes, B. Herman and B. Tondu, "Rehab robotics open-loop identification of a two degrees of freedom rehabilitation robot actuated by pneumatic artificial muscles", *20th national Day of Biomedical Engineering* (20th NDBME), Brussels, 15th February 2022.

[10] N. Hogan, "Adaptive control of mechanical impedance by coactivation of antagonistic muscles", *IEEE Transactions on Automatic Control*, vol. AC-29, n°8, 1984, pp. 681-690.

[11] B. Tondu and P. Lopez, "Modeling and Control of McKibben Artificial Muscle Robot Actuators", *IEEE Control Systems Magazine*, Vol. 20, n°2, 2000, pp. 15-38.

[12] B Tondu, S Ippolito, J Guiochet and A Daidie, "A seven-degrees-of-freedom robot-arm driven by pneumatic artificial muscles for humanoid robots", *The Int. J. of Robotics Research*, vol. 24, n°4, 2005, pp. 257-274.

[13] B. Tondu, "Static modeling of pneumatic artificial muscle actuator", *IEEE 5th Int. Conf. on Soft Robotics (RoboSoft)*, Edinburgh (Scotland), April 2022, pp. 364-369.

[14] J. Sapin and M. Joly, "REAplan, Manuel d'utilisateur", *Axinesis Advanced Rehabilitation*, 2022.

[15] J. Guiaux Brinon, "Rehab robotics: control and validation of an upper-limb rehabilitation robot actuated with artificial muscles", *Master Thesis*, Université Catholique de Louvain-la-Neuve (Belgium), June 2022.

[16] M. radmilovic, D. Urukalo, M.M. Jankovic, T.J. Dimkic Tomic, M. Trumic and K. Jovanovic, "Elbow joint stiffness functional scales based on Hill's muscle model and genetic optimization", *Sensors*, vol. 23, 1709, 2023 (22 pages).

[17] M. Baggetta, G. Berselli, G. Palli and C. Melchiorri, "Design, modeling, and control of a variable stiffness elbow joint", *The Int. J. of Advanced Manufacturing Technology*, vol. 112, 2022, pp. 4437-4451.