Adaptive Bio-kinematic Control for Secure Rehabilitation Robotic Devices

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I. INTRODUCTION

Rehabilitation robotics, such as exoskeletons, requires a control interface for the direct transfer of mechanical power and the exchange of information in order to assist the patient in his/her movements. However, the available control methods do not take into account the patient's expertise and muscle abilities, causing pain during rehabilitation [1]. Building on previous works [2] on designing and manufacturing a rehabilitation skeleleton that has two active degrees of freedom on the hip and knee, the objective is to find the ideal control strategy. In this work, we propose using an interactive neuro-motor method derived by muscular co-contraction indexes (CCI) to benefit from bio-kinematic for lower-limb exoskeleton control [3]. The novel dynamic index called neuro-motor index (NMI) is introduced to estimate the relation between muscular co-contraction derived from electromyography signals (EMG) and joint angles [4]. To enhance the precision of the NMI, we describe an estimation method relying on an analysis of canonical correlation (CCA). CCA is applied online, at NMI determined from the patient , and healthy joint angles (hip and knee), during successive gait cycles of patients, and used for a high-level loop of a controller, allowed to have the best margin of compensation, which will then be the input for another low-level PID control loop linked to the exoskeleton actuator. According to this method, the compensation angle input, corresponding to the correction angle, gives the user desired exit angles in the control chain, depending on the capabilities of the patient and without pain, in a gradual way. The contributions were as the following:

- Introduction of a new index for bio-kinematic control.
- A new methodology relying on machine learning in the control strategy.

II. MATERIALS AND MEASUREMENTS

A. Subjects and data acquisition

Nine healthy subjects, without a history of neuromusculoskeletal impairments, 7 subjects with stroke and 5 with cerebral palsy (PC), were recorded in Gait Laboratory (Raymond Poincare Hospital, Garches, France). A bio-kinematics study was conducted in a large room; where the patients walked a straight line for 10 meters, for different velocities and for 11 gait cycles at each velocity, the acquisition system includes: Video equipment; An optoelectronic system to measure the joint angles of the knee and the hip (left and right); Ground force platforms to record dynamic Data; An electromyographic system to record muscle activity where the electrodes were placed at the level of two biarticular muscle groups (quadriceps and hamstrings) for the knee and the hip on each leg (left and right). Everything was synchronized and connected to a computer for data acquisition.

B. Method

In this study, using Matlab code, raw EMG signals are filtered with a band-pass filter (10-400 Hz), tt and finally filtered with a 4th order Butterworth low-pass filter (4-6 Hz) and normalized by the detected maximal voluntary contraction (MVC). Then, to build NMI, EMG envelopes are calculated for both agonistic and antagonistic muscles. The maxima and minima of the joints angular curves were detected to extract a non-linear regression from the intersection between the pair of chosen muscles:

$$INM = A(t)[\frac{1}{B(t)} + \frac{Rx(t)}{C(t)}] \tag{1}$$

$$A(t) = \int_{t1}^{t2} (ENV_{emg-ago}(t) \cap ENV_{emg-anta}(t)dt) \tag{2}$$

$$B(t) = \int_{t1}^{t2} (ENV_{emg-ago}(t) \cup ENV_{emg-anta}(t)dt). \tag{3}$$

$$C(t) = \int_{t1}^{t2} (ENV_{emg-ago}(t) + ENV_{emg-anta}(t)dt). \tag{4}$$

where t_1 and t_2 denote the period of one complete gait cycle. Rx(t) is a non-linear regression derivited by Hermitian polynomial applied on $ENV_{emg_{ago}} \cap ENV_{emg_{anta}}$, by the detection the envelop peak of a muscle pair (agonist/antagonist) during each flexion/extension of a gait cycle, and to estimate the specific joint trajectory angle. In order to obtain a better margin of angular variation from NMI for several successive data input, the CCA is applied on healthy gait angles as a reference and the NMI determined by the data extracted during gait, from patient with neurological disorders (PC or stroke). This operating diagram is visible in 1. The NMI is determined from the EMG for the pair of muscles (agonist/antagonist), and Θ_{ref} represents the walking angles of a healthy subject. The linear combinations of I and Θ_{ref}

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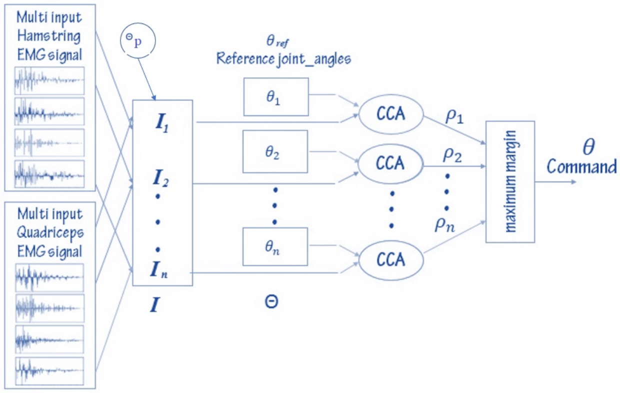

Fig. 1. Illustration of the ACC applied to I, which is the index determined from EMG signals, and the joint angles.

are $I = I^T W_I$ et $\Theta_{\text{ref}} = \Theta^T W_\Theta$, respectively. CCA finds weight vectors, W_I and W_Θ, which maximize the correlation between I and Θ, by solving the following optimization problem:

$$\max_{(W_I,W_\Theta)} \rho(I,\Theta) = \frac{E(I^T\Theta)}{\sqrt{E(I^T I)E(\Theta^T\Theta)}} \tag{5}$$

$$= \frac{E(W_I^T I I^T W_\Theta)}{\sqrt{E(W_I^T I I^T W_I)E(W_\Theta^T \Theta\Theta^T W_\Theta)}} \tag{6}$$

where ρ_n are the ACC coefficients obtained with the angle of reference signals $\theta_1, \theta_2, ..., \theta_n$. The maximum ρ with respect to W_I and W_θ is the maximum canonical correlation. The projections on W_I and W_θ, ie I and θ, are called canonical variants. NMI determines an angle according to the capacity of the muscles. CCA determines the matrix of correlative coefficients ρ between the angle determined by the NMI and the healthy angle, which helps to correct false angles and obtain the new trajectory to follow θ_d. θ_d will then be an entry in a low-level loop containing a PID controller. CCA leads us to the best margin of compensation according to muscular capacity and the expertise of the patient.

III. RESULTS AND DISCUSSION

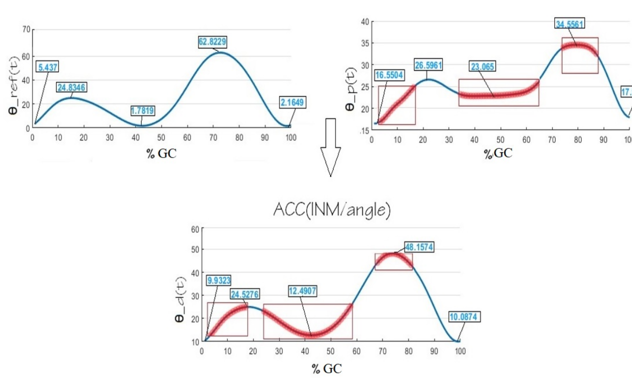

Fig. 2. Illustration of the reference healthy angle, the angle of a stroke subject and the corrected angle offered by the INM for control using CCA (right knee at spontaneous speed)

TABLE I

THE CORRECTION RATE OFFERED BY NMI FROM CCA OF THE RIGHT KNEE FOR A STROKE SUBJECT

Angle	F1	E1	F2	E2
$\theta_{ref}(t)$	5.4° to 24.8°	24.8° to 1.8°	1.8° to 62.8°	62.8° to 1.5°
$\theta_p(t)$	16° to 26.5°	26.5° 23°	23° to 34.5°	34.5° to 18°
$\theta_d(t)$	10° to 24.5°	24.5° to 12°	12° to 48.2°	48.2° to 10°
%	34%	45%	50%	48%

As it could be seen on Fig.2 for the right knee (stroke subject), NMI improved the quality of the start, and limited the first flexion to 24.5° which is suitable with θ_{ref} instead of 26.5° given by the patient, he corrected the extension which is so destroyed until reaching 12.5° instead of 23° which is acceptable despite the fact that so far from θ_{ref} in this part of the cycle, a correction towards the end of the second flexion and at the beginning of the last extension appears at the time level or $\theta_p(t)$ sup $\theta_{ref}(t)$ and took more time passing from flexion to extension, even for the angle which is improved until reaching 48 ° instead of 34.5 ° where it is worth θ_{ref} 62.8 °, finally the return is 10 ° instead of 17 ° and that is 2 ° for θ_{ref} and it depends on the spasticity in the patient.The correction rate offered by NMI from CCA, for this patient, reaches 45% . Finally, 11 neurological patients (with PC and stroke) were testing, the correction rate was achieved to 82% in some cases for the kinematic curves of the hip and knee.

IV. CONCLUSION

NMI is a new bio-kinematic index, producing a reliable and generic estimation of the articulation flexion/extension using EMG signals to determine muscle co-contraction. The main contribution of this index is to provide an estimation of the walk cycle without imposing are-defined trajectory for the patient. The patient is considered as an expert, providing its own optimal gait cycle for calibration, and the NMI yields a robust index for designing an exoskeleton controller. It is then integrated into the control scheme of a lower limb exoskeleton used as walking assistance for people suffering from spasticity. The control input is the compensation angle calculated online-based on the NMI and CCA and depending on the patient's online-measured gait angle.

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