In-vivo Estimation of the Human Elbow Joint Dynamics during Passive Movements Using Musculo-skeletal Model Computations

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***Abstract*— Due to specialists doctors demand of quantifying some indicators to be used during examination, an original painless solution to estimate in-vivo the human joint passive rigidity is proposed and applied to the elbow joint. It is based on the use of a musculo-skeletal dynamics computation and a linear modelling of the human elbow joint dynamics. Movements acquisition is performed in a motion capture studio during common medical examination for neuro-motor disease. Rigidity of the joint is the linear least square solution of the obtained dynamic system. This method enable the use of indexes such as the condition numbers or the relative standard error that are useful to give interpretation of the results.**

***Index Terms*— passive joint dynamics, muscculo-skeletal human model, identification, motion capture**

I. Introduction

Understanding of the human body due to the developments of miniaturizing technics and the advanced in nano-scale has dramatically increased this past years, though the understanding of some functions are not clear yet. More particularly the understanding of the brain and the neural system are still challenging issues and their disorders are difficult to diagnosis, medicate and to follow objectively. New tools have became essential to help doctors and specialists in the first diagnosis of neuro-motor disorders and all along the treatment of patients suffering from slow evolutional diseases such as Parkinson disease. Therefore there is a great demand in solutions to quantify the alterations in order to complement the clinical examinations since it is difficult to have a clear appreciation of occurring changes at each examination. However bio-mechanical or biological in-vivo solutions usually use expensive, non flexible or painful experiments which make both doctors and patients very reluctant. As a matter of fact this paper focuses on the passive dynamic parameters of the limbs and proposes an original painless solution to estimate in-vivo the human limbs joints rigidity for passive movements with only a motion capture studio. For medical applications purpose the estimation is achieved with common test performed during examination of Parkinson's suffering patients and applied to the elbow joint. This method is widely applicable to all the human limbs joints. It is based on the use of a musculo-skeletal dynamics computation and a linear modelling of the human elbow joint dynamics: stiffness, viscosity and friction. Inertial parameters of the arm must previously be estimated using multi-body description of the arm and linear property of the inverse dynamic model in the inertial parameters [1] or using scaling. The sampled linear over-determinate system obtained along exciting movements, designed for that purpose or from medical examination, is solve with least square method allowing to compute the standard deviation statistically and the condition number of the observation matrix to interpret the obtained results. Finally experimental setup is described and experimental results for several valid subjects are given and discussed.

II. Medical context, the case of the Parkinson disease

Parkinson disease (PD) that was first described in 1817 by James Parkinson, is a common neurological disorder which incidence rises after the age of 50, such that about 2% of the elderly in the developped countries are affected. The disease is due to the striatal deficiency of dopamine neurotransmitter following neuronal degeneration within the substantia nigra. Dopamine plays an important role in controlling muscle movements, consequently affected people experience trembling, muscle rigidity, slowed motion, difficulty in walking, problems with body balance and coordination, smaller handwriting, drooling. It is a slowly progressive, degenerative disease that takes 10 to 15 years from initial diagnosis to later stages. Though earlier stages does not affect much daily life, at the latest stage the affected persons lose the ability to control their movements, making everyday activities hard to manage. The intellect too is affected by the disease. Patients suffer impaired speech, memory and attention problems, dementia, anxiety or depression, or problems with autonomic functions such as blood pressure [2].
The diagnosis of PD is a clinical one: it is based on the patient medical history, observations of his symptoms, and

a neurologic examination. There are no confirmatory tests. During the medical diagnosis doctor take special care to the following items:

- Rest tremor of a limb: shaking with the limb at rest,
- Slowness of movement: bradykinesia,
- Rigidity: stiffness, increased resistance to passive movement of the limbs or trunk,
- Poor balance: postural instability.

At the moment, the diagnosis of muscles diseases or neuromotor disorder such as Parkinson disease, by doctors, consists in performing a set of tests and examinations on the patient that must reveal by observation the above symptoms, more particularly rigidity and postural instability. Table II gives a non exhaustive list of those tests. They are separated in two types: passive tests and active tests. In the passive tests (P1 to P5) the patient is not moving by himself but movements can be induced by the specialist. Muscles do not contract. While during the active tests (A1 to A6) the patient is asked to perform some movements by himself thus muscles contract.

TABLE I

TESTS PERFORMED BY DOCTORS DURING DIAGNOSIS OF MUSCLE OR NEURO-MOTOR DISEASES

	Passive movements
P1	standing in normal position with eyes closed
P2	standing in normal position with open eyes
P3	standing joint feet with open eyes
P4	arm lifted and released by doctor
P5	upper body shaken by doctor [1]
	Active movements
A1	normal walk volte-face normal walk
A2	walk on tip toe
A3	walk on heel
A4	lying on the back and rising up
A5	rising from sat position
A6	small jump

[1] It consist in giving rotational impulsion around the vertical axis to the shoulder of the patient and observing the free movements of the arms as shown in Fig.1.

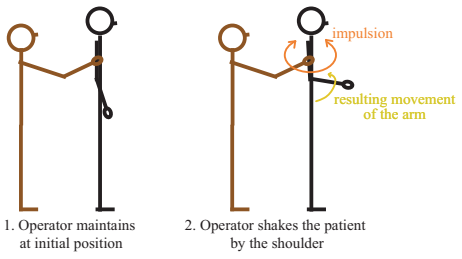

Fig. 1. Experimental process: movements achieved during medical diagnosis, patient standing, operator giving impulsion to him by the shoulders

III. MODELLING OF THE HUMAN BODY

Powerful robotics formalisms, such as Modified Denavit Hartenberg formalism [1], allow to describe systems as multi-body systems linked by joints. Such description has been successfully applied to many kind of systems [3], [4], [5] with complex structures: tree or parallel. Though taking into account the high number of degrees of freedom of the human body and the changes that can occur in the kinematics chain, such formalisms have been enhanced and developed for the specific human body, based on musculo-skeletal approach [6], [7]. Those modelling allow to compute easily the inverse kinematics as well as the inverse dynamics for the whole human body with 366 muscles driving a skeleton with 155 degrees of freedom (DOF).

$$\boldsymbol{\Gamma} + \boldsymbol{Q} = \boldsymbol{\Gamma}^e + \boldsymbol{\Gamma}^v + \boldsymbol{\Gamma}^f + \boldsymbol{H}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}, \boldsymbol{D}_P\right) \tag{1}$$

where:

- $\boldsymbol{q}$ the vector of joint angle q_j, $\dot{\boldsymbol{q}}$ and $\ddot{\boldsymbol{q}}$ its first and second time derivatives,
- j denotes the concerned joint in the chain and the following body attached to it,
- $\boldsymbol{D}_P$ the vector of inertial parameters of the system: mass, inertia, first moment of inertia,
- $\boldsymbol{\Gamma}$ is the vector of joint forces or torques
- $\boldsymbol{Q}$ is the vector of generalized efforts representing the projection of the external forces and torques on the joint axes, it is calculated with:

$$\boldsymbol{Q} = -\sum \boldsymbol{G}_j(\boldsymbol{q})^T \boldsymbol{F}_{ej} \tag{2}$$

- $\boldsymbol{G}_j(\boldsymbol{q})$ is the Jacobian matrix of the frame of body j
- $\boldsymbol{F}_{ej}$ is the vector of external forces and moments applied by body j on the environment,
- $\boldsymbol{H}$ is the vector of inertial, Coriolis, centrifugal and gravity forces,
- $\boldsymbol{\Gamma}^e$ is the joint elastic force. The j^{th} element of $\boldsymbol{\Gamma}_e$ is written as:
  - if j has elasticity:

$$\Gamma_j^e = k_j(q_j - q_j^r) \tag{3}$$

    with k_j the stiffness of joint j, q_j^r the rest joint angle,
  - if j is not an elastic joint $\Gamma_j^e = 0$
- $\boldsymbol{\Gamma}^v$ is the joint viscosity force with h_j the viscous coefficient:

$$\Gamma_j^v = h_j \dot{q}_j \tag{4}$$

- $\boldsymbol{\Gamma}^f$ is the friction force. It is modelled by Coulomb coefficient f_j:

$$\Gamma_j^f = f_j sign(\dot{q}_j) \tag{5}$$

As mentioned above the inertial parameters $\boldsymbol{D}_P$ are known. They can be estimated from previous experiments or scaled from literature's available parameters [8]. Moreover the estimation is achieve for passive movements of the joints , though $j = n_j$ and the external forces $\boldsymbol{F}_{ej}$ is null in (2), consequently $\boldsymbol{Q} = \boldsymbol{0}$. (1) then becomes for each joint j:

$$\boldsymbol{\Gamma}_j - \boldsymbol{H}_j\left(\boldsymbol{q}_j, \dot{\boldsymbol{q}}_j, \ddot{\boldsymbol{q}}_j, \boldsymbol{D}_{Pj}\right) = k_j(q_j - q_j^r) + h_j\dot{q}_j + f_j sign(\dot{q}_j) \tag{6}$$

where the left side is known: inertial effects of the arm, and the right one contents the joint dynamic parameters to estimate: k_j, h_j and f_j.
The model is linear in the parameters to estimate and can be written as:

$$\boldsymbol{T} = \boldsymbol{D}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}\right) \boldsymbol{X} \tag{7}$$

- $\boldsymbol{X}$ the $(3n_j \times 1)$ vector of parameters to be estimated, $\boldsymbol{X} = [\boldsymbol{X}_1 \ \ldots \ \boldsymbol{X}_j \ \ldots \ \boldsymbol{X}_{n_j}]$ where $\boldsymbol{X_j} = [k_j \ h_j \ f_j]^T$
- $\boldsymbol{D}$ is the $(n_j \times 3n_j)$ vector function of joint angle q and its first and second derivatives,
- $\boldsymbol{T}$ is computed by $\boldsymbol{\Gamma} - \boldsymbol{H}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}, \boldsymbol{D}_P\right)$

This system is solved using linear least square optimization techniques [1], [9]. The dynamic model (6) is sampled along an exciting movement. All the n_e samples give a linear system of equations:

$$\boldsymbol{Y} = \boldsymbol{W}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}\right) \boldsymbol{X} + \boldsymbol{\rho} \tag{8}$$

where:

- $\boldsymbol{Y}$ is the $(n_e n_j \times 1)$ vector of joint torques, obtained by sampling $\boldsymbol{T}$
- $\boldsymbol{W}$ is the $(n_e n_j \times 3n_j)$ observation matrix (or regressor matrix), obtained by sampling $\boldsymbol{D}$
- $\boldsymbol{\rho}$ the $(n_e n_j \times 1)$ vector of modelling errors.

Finally, (8) is solved using the least squares which is implemented in many software packages with efficient algorithms (Matlab, Scilab). Standard deviations on the estimated values $\sigma_{\hat{X}j}$ are computed using classical and simple results from statistics, considering the matrix $\boldsymbol{W}$ to be a deterministic one, and $\boldsymbol{\rho}$ to be a zero mean additive independent noise, with standard deviation σ_ρ such that:

$$\boldsymbol{C}_{\rho\rho} = E(\rho^T \rho) = \sigma_\rho^2 \boldsymbol{I}_{n_e \times 1}$$

where E is the expectation operator.
An unbiased estimation of σ_ρ is used:

$$\sigma_\rho^2 = \frac{\| \boldsymbol{Y} - \boldsymbol{W}\hat{\boldsymbol{X}} \|^2}{n_e - 3} \tag{9}$$

The covariance matrix of the estimation error and standard deviations can be calculated by:

$$\boldsymbol{C}_{\hat{X}\hat{X}} = E\left((\boldsymbol{X} - \hat{\boldsymbol{X}})(\boldsymbol{X} - \hat{\boldsymbol{X}})^T\right) = \sigma_p^2 (\boldsymbol{W}^T \boldsymbol{W})^{-1} \tag{10}$$

$\sigma_{\hat{X}j} = \sqrt{\boldsymbol{C}_{\hat{X}\hat{X}}(j,j)}$ is the i^{th} diagonal coefficient of $\boldsymbol{C}_{\hat{X}\hat{X}}$. The relative standard deviation $\sigma_{\hat{X}j}\%$ is given by:

$$\sigma_{\hat{X}j}\% = 100 \frac{\sigma_{\hat{X}j}}{| \hat{X}_j |} \tag{11}$$

Assuming that $\sigma_{\hat{X}j}$ is the realization of a Gaussian random variable, the 95% confidence interval is $2\sigma_{\hat{X}j}$ and the relative confidence interval is $2\sigma_{\hat{X}j}\%$. Then we consider that a parameter with a relative confidence interval lower than 10% is well identified, keeping in mind that this is only an indicator based on statistical assumption. The parameters which are not good identified may be not excited by the identification trajectory, or may have small effect on the dynamic model and can be removed [10]. But it is to be noted that this criterion is not a deterministic one particularly for parameters with small values, where they may be good identified although $\sigma_{\hat{X}j}\%$ is more than 10.

IV. Experimental setup

Such formalism is thus used for the human arm and the elbow joint. It (Fig.2 left) has 2 mainly rotational degrees of freedom of about $180°$ range for each that allow the hand to move widely: pronation/supination is the rotation around $\boldsymbol{z_{PS}}$ and flexion/extension is the rotation around $\boldsymbol{z_{FE}}$ axis (varus/valgus the rotation around $\boldsymbol{z_{VV}}$ is essentially fixed and consequently not considered).

This paper focuses on flexion/extension (F/E) of the elbow joint. General equation of the inverse dynamic model given by (1) is applied to the elbow joint flexion extension as a one degree of freedom joint with elasticity ($n_j = 1$). The vector of parameters to estimate is then $\boldsymbol{X} = [k \ h \ f]^T$.

The estimation of the human joint elbow dynamics in-vivo, with no pain and distress to the subject only requires a motion capture studio and optical markers. It makes the methods widely applicable for medical diagnosis and feasible for patients.

A. Motion capture system

Experiments can be conducted in any equipped motion capture studio. The optical motion capture system used is composed of ten high resolution cameras. Reflective markers are arranged on the subject body as shown Fig.2. The whole system is capable of capturing the reflective marker's position at $30\,fps$ along, if needed EMGs data can be synchronously recorded at $1\,KHz$. High speed cameras ($120\,fps$) could have been used but they don't provide better results and post-treatment of markers labelling is longer.
Five optical markers, from the shoulder to the hand, are necessary to record the elbow joint movements accurately. Three more markers, on the opposite shoulder and both hips, are used to define the trunk posture (Fig.3), for a more accurate computation of the inverse kinematics.

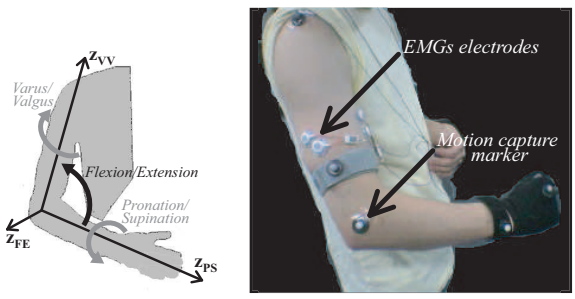

Fig. 2. The elbow joint degrees of freedom (left) and the experimental equipment: optical markers, EMGs of Biceps and Triceps are optional (right)

B. From markers position to joint angle

The inverse kinematics model is computed by a musculo-skeletal model of the human body (Fig.3) directly from the motion capture data. Joint angles q is computed by an algorithm similar to UTPoser [11]. It computes a natural posture that satisfies the given marker positions.

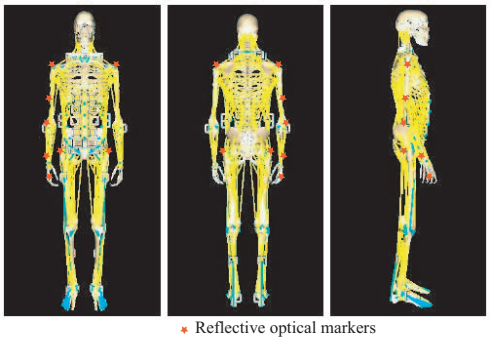

Fig. 3. Musculo-skeletal human model and markers position: 2 markers on the right and left shoulder on the Acromio-Clavicular joint, 1 marker at the 2/3 of the upper arm, 1 marker on lateral Epicondyle, approximative elbow joint axis, 1 marker at the external $2/3$ of the forearm between Radius and Cubitus, 1 marker on the dorsum of the hand between heads of 3^d and 4^{th} metacarpal, 2 lateral markers on the right and left Illiac crest of the hip bone.

C. Exciting movements for the estimation

In order to develop a widely applicable method to quantify the passive rigidity of the human body the passive movements performed during the diagnosis of neuromuscular disease and particularly PD given in Table II must be used. The most appropriate movement for the estimation of elbow rigidity is P5, described Fig. 1. Movements are passive if muscles involved are not neurally activated. EMGs (ElectroMyoGraphies) of the main muscles of the arm: Biceps and Triceps, are then recorded to insure that no muscle is activated during the exciting movements used for the experimental estimation. Full wave rectified, filtered (by a 2^d order feed and forward Butterworth with $6\,Hz$ cut-off frequency) and normalized records during test P5 are given Fig.4 for the Biceps and the Triceps: the neural activity is about 2% for each muscle which shows that muscles are not activated. A good estimation of

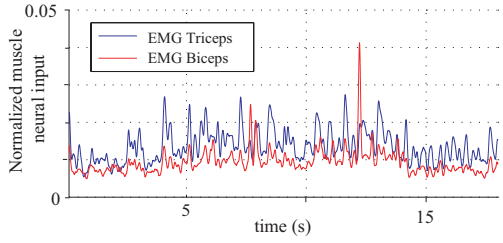

Fig. 4. Level of normalized (0<u<1) muscle neural input of the Biceps and the Triceps during the medical diagnosis

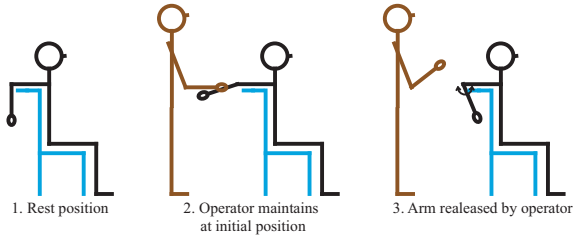

Fig. 5. Experimental process: exciting movement for the joint elbow dynamics: patient seated, operator helps conducted the experiments

dynamics requires a movement where all the dynamics to be estimated are excited which correspond to a condition number of the observation matrix $\boldsymbol{W}$ close to 1. An other test with good exciting properties but not use in medical diagnosis is to maintain the sat patient shoulder at $90°$ to the back and forearm vertical at rest. The forearm is lifted and then released by an operator, as shown in Fig.5. Despite such a movement is appropriated to estimation but difficult to be performed by aged people, therefore it has been used here to check the consistency of the results obtained with the P5 test.

V. Experimental identification of the elbow joint dynamics

To conduct the experiments in the aim of the estimation of the human elbow joint dynamics two valid volunteers are equipped with optical markers and are taught about both experimental process. A muscle diseases practitioner performs a full medical diagnosis check-up on both subjects. All movements are captured. Joint angles are computed from the inverse kinematics as above and inverse dynamic model (8) is computed and solved with least square method. Standard deviation is by the way computed following (11).
Test P5 described above is used for the estimation of the elbow joint passive dynamics. Practitioner performs it several time, identification results are similar for each test, consequently results are given in Table II for subject 1 and Table III for subject 2 are the one obtained with one of the test P5. The non medical exciting test is also performed with an operator to achieve relaxed movements. This movement is repeated and recorded 2 to 4 times in order to assure a good repeatability. Estimation is carried out with concatenation of all the movements recorded to give about 1100 samples. Both tests have been achieve separately within one month.

The above results show that condition numbers of the observation matrix $\boldsymbol{W}$ are small and close to one and proves relatively good exciting properties of both tests. According to the low value of the relative standard deviation $\sigma_{\hat{X}_j}\% < 1$ the stiffness k of the elbow joint can be estimated with very good accuracy for both subject. The joint viscosity is also estimated with good accuracy too $\sigma_{\hat{X}_j} < 10$ for the non medical test though for the medical test $\sigma_{\hat{X}_j}\% > 10$ but

value are similar to the other one and very low. Ones can concluded in a poorer excitation of the viscosity with the medical test P5. For friction the value estimated is very low consequently the relative standard deviation $\sigma_{\hat{X}j}\% > 10$, it is then impossible to concluded from analyzing the relative standard deviation. What can only be said, according to the similarity of the results for both subjects is that that friction in joint elbow is very low: less than 5% of the joint torque.
Results obtained can be compared to literature which gives average data with few details about gender, size, age or condition and it is to be noted that the size and mass of the subject in literature are different from those of our subjects. Average stiffness of elbow joint given by Stroeve in [12] is $1.5\ Nm/rad$ which confirmed the obtained results. Average viscosity is $0.2\ Nms/rad$ which can be discussed from the differences noted above and that literature viscosity term also includes the viscosity term due to co-activated muscles. The estimation with the medical diagnosis movement is possible, but movement could be enhanced to excite more the viscosity and friction parameters.

Finally, Fig.6 to 9 give the joint torque measured $\boldsymbol{Y}$ and the joint torque estimated from joint angle and elbow dynamics: $\boldsymbol{W}\hat{\boldsymbol{X}}$. Error $\boldsymbol{Y} - \boldsymbol{W}\hat{\boldsymbol{X}}$ is also given (black dotted line). Direct validations are given Fig.6 and 7, cross validations for two passive movements not used for the estimation are given in Fig.8 for the subject 1 and Fig.9 for subject 2. Both validation give low error between the measured torque angle and the estimated one from the joint dynamics identified which confirms the interpretation of the obtained results.

VI. Conclusion

This paper proposes an original, non invasive and easy solution for direct in-vivo estimation of passive joint dynamics for medical applications in the diagnosis of muscle disease and neuro-motor disorders such as Parkinson disease. It is based on the medical examination tests performed during the diagnosis of such diseases and on the use of the kinematics computation of musculo-skeletal model of the human body coupled with a motion capture studio. The joint dynamic model used is linear in the stiffness, viscosity and friction. The dynamic model is sampled along the exciting passive movement to obtain an over-determinate system which is then solved with least-square method. Experimental results presented here show that estimation is successful despite only two subjects are tested. Interpretation is confirmed by the low value of the standard deviation for stiffness and viscosity, and by the low relative error of estimated joint torque from identified dynamics on validation figures. Stiffness results are also consistent with literature data. Though the medical movements could be enhanced to excite more the viscosity of the concerned joint. Such results are very important for muscle and neuro-motor specialists as they give a quantification of the rigidity of the body to a clinical test. Moreover the passive behavior of joints is intrinsically linked to the muscles and the neural input: stiffening of muscles such as occurs in Parkinson disease implies global stiffening of the passive movements of the joint but changes are visually difficult to notice.
This method will be extend to the whole upper limbs joints using the multi-body description. Thus wrist, elbow and shoulder dynamics of both side can be simultaneous estimated. The linear least square method could be enhanced using weighting procedure for simultaneous multi-joint estimation. Finally the method will be applied to a larger population including diseased people and evolution over time of those

TABLE II

Results of the estimation for subject 1

parameter	unit	Medical test P5 $\hat{\boldsymbol{X}}$	Medical test P5 $\sigma_{\hat{X}j}\%$	Non medical test $\hat{\boldsymbol{X}}$	Non medical test $\sigma_{\hat{X}j}\%$
Stiffness k	Nm/rad	2.951	0.179	2.609	0.29
Viscosity h	Nms/rad	0.031	21.7	0.049	7.47
Friction f	Nm	-0.015	30.1	-0.017	25.38
Cond$\boldsymbol{W}$		2.3		2.91	
n_e		700		1100	

TABLE III

Results of the estimation for subject 2

parameter	unit	Medical test P5 $\hat{\boldsymbol{X}}$	Medical test P5 $\sigma_{\hat{X}j}\%$	Non medical test $\hat{\boldsymbol{X}}$	Non medical test $\sigma_{\hat{X}j}\%$
Stiffness k	Nm/rad	2.043	0.35	2.238	0.25
Viscosity h	Nms/rad	0.025	25.39	0.029	9.39
Friction f	Nm	-0.01	68.16	-0.012	20.9
Cond$\boldsymbol{W}$		2.2		3.11	
n_e		450		1100	

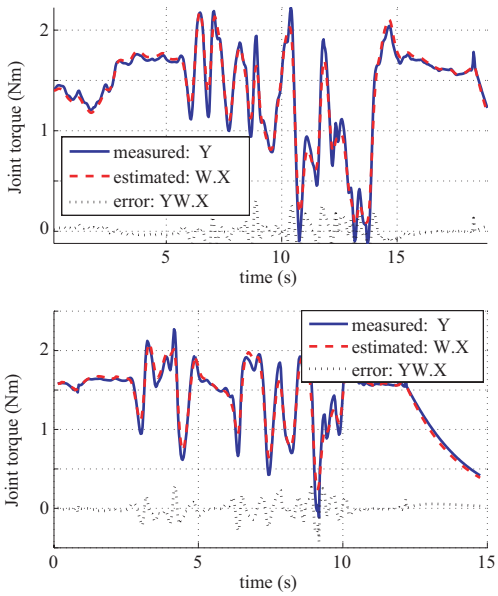

Fig. 6. Direct validation: medical diagnosis movements P5 for subject 1 (top), for subject 2 (bottom)

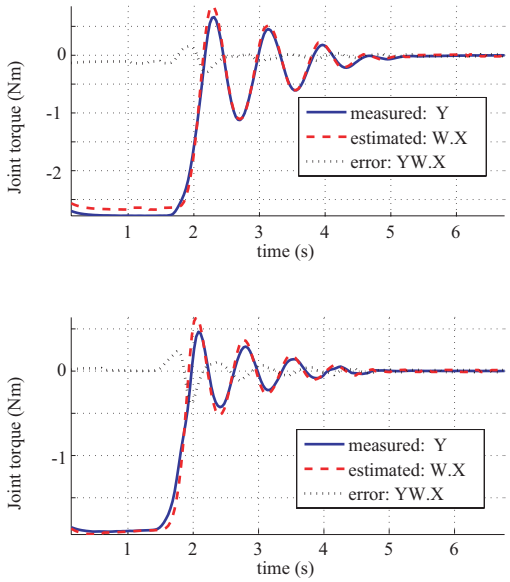

Fig. 7. Direct validation with non medical test for subject 1 (top), for subject 2 (bottom)

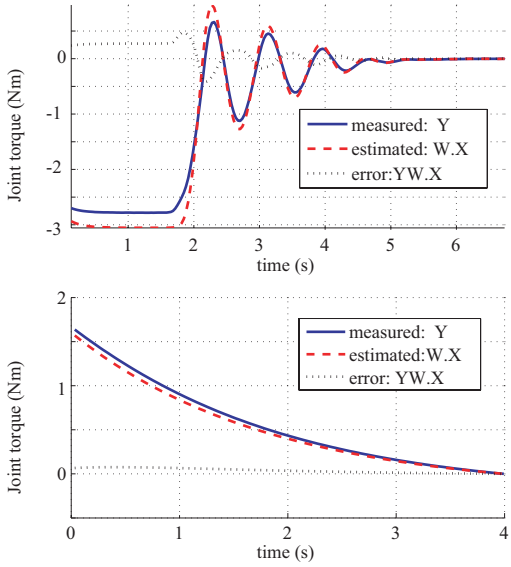

Fig. 8. Cross validations, for subject 1, of the results estimated with the medical diagnosis test for two different tests: swing of the forearm similar to non medical test (up), other movement during the medical diagnosis (bottom)

diseased people will be studied. The constant linear joint model should be discussed and the use of non linear least-square optimization procedure is to be considered.

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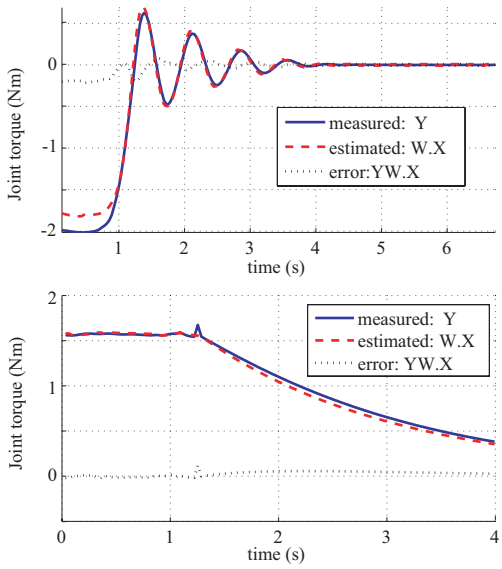

Fig. 9. Cross validations, for subject 2, of the results estimated with the medical diagnosis test for two different test: swing of the forearm similar to non medical test (up), other movement during the medical diagnosis (bottom)

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