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# Identifying Musculo-tendon Parameters of Human Body Based on the Musculo-skeletal Dynamics Computation and Hill-Stroeve Muscle Model

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*Abstract*— **The goal of the works presented in this paper is to study the feasibility of the in-vivo estimation of the musculo-tendon dynamics using an original approach. Contrarily to usual literature in this field the Hill-Stroeve based model parameters are estimated, and not only some global parameters with little physiological meaning. This estimation is based on the computation of the inverse kinematics and the inverse dynamics of the human body, using a musculo-skeletal description. It also includes an optimization of the muscle force. Muscles are described by a modified and simplified Hill-type model. Parameters involved in this model are estimated in-vivo. In the preliminary works the flexion-extension of the elbow joint only is considered. Experimental set-up includes EMGs acquisition and motion capture data. Movements are chosen to limit co-contraction of antagonist muscles. Results are given for three of four muscles involved in the joint movements. Such results are very important for medical applications in rehabilitation, sport science, study of muscle diseases...**

## I. Introduction

Robots get closer to human due to the miniaturization of components and the developments of artificial organs such as muscles and the enhanced computation power. Although the human body is very complex and the ability of movement is very wide which make its comprehension more difficult. For a clear understanding of the human dynamics and to generate smooth movements it is very important to have a good knowledge of the human anatomy and of its dynamics. Though actuators of the human body are the muscles, their dynamics is very important in the study of the human body movements. Its complexity is mainly due to its biologic nature, the high number of muscles and degrees of freedom and also because of the differences between each human being: size, mass, strength, capacity... which are closely related to the history of the subject: doing sports, having had injuries... In dynamic modelling it is important that the model used gives a realistic description of the behavior and that this model is adapted to the subject. For this reason the subject specific musculo-tendon's dynamics must be estimated. The model used for the muscle modelling is based on the Hill-Stroeve model, known to be the most accurate model to describe the complex muscle dynamics, and related to the micro-structure of the muscle. Unlike usual works on the human body where this model is globally scaled to the subject, the proposed method focuses on the subject-specific parameters involved in this model. Previous simulation results have shown that it is technically possible to estimate those dynamic parameters of the muscles. This paper first presents a sum up of the dynamic modelling of musculo-tendon complex based on the Hill-type modelling (Section II). Then in the third section a simple modelling of the elbow joint, considering one degree of freedom, is given. The fourth section presents the experimental set up based on the use of EMGs measurements and motion capture system. Finally the fifth section gives the identification method, some simulation results and the preliminary experimental results.

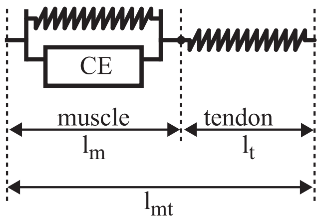


Fig. 1. Musculo-tendon complex without pinnation angle

## II. Musculo-tendon complex dynamics

The musculo-tendon complex is composed of the tendon and the muscle (Fig.1). The tendon is a passive wire that does not generate movement. The muscle is an active contractile element (generally noted CE) that generates contraction of the muscle controlled by neural excitation and then its lengthening or its shortening. Contractions of the muscle are assumed to be iso-volume [1].

### A. Musculo-tendon complex dynamics modelling

The musculo-tendon dynamics is function of the muscle activity $a(t)$, and the length and velocity of the muscle and the tendon, respectively $l_m$, $\dot{l_m}$, $l_t$ and $\dot{l_t}$. The model given here is a simplification of the one described in [2]: the pinnation angle, angle between the muscle and the tendon, is neglected. The force $F_m(t)$ developed by the muscle is given by a function of the muscle activity $a(t)$, the muscle length $l_m(t)$, the contraction velocity of the muscle $\dot{l_m}(t)$ and the maximal isometric force $F_{max}$ at full activation ($a(t) = 1$). It can be separated in four terms as follow:

$$F_m = a(t) f_l(l_m) f_v(\dot{l_m}) F_{max} \tag{1}$$

where $f_l$ is the force-length relation and $f_v$ is the force-velocity relation given by:

$$f_l(l_m) = exp\left(-\left(\frac{l_m - l_m^0}{l_m^{sh}}\right)^2\right) \tag{2}$$

with
$l_m^0 = l_m^{min} + L_m^{opt}(l_m^{max} - l_m^{min}) - l_t^0$
$l_m^{sh} = L_{sh}(l_m^{max} - l_m^{min})$

$$f_v(\dot{l_m}) = \begin{cases} 0 & \text{if } \dot{l_m} \leq -v_{max} \\ \frac{V_{sh}\left(v_{max} + \dot{l_m}\right)}{V_{sh} v_{max} - \dot{l_m}} & \text{if } -v_{max} \leq \dot{l_m} \leq 0 \\ \frac{V_{sh} V_{shl} v_{max} + V_{ml} \dot{l_m}}{V_{sh} V_{shl} v_{max} + \dot{l_m}} & \text{if } \dot{l_m} \geq 0 \end{cases} \tag{3}$$

where $v_{max}$ is the maximum contraction velocity, $V_{sh}$ determining the concavity of the Hill curve during shortening, $V_{shl}$ determining the concavity of the Hill curve during lengthening, $V_{ml}$ the maximum velocity during concentric contraction. $l_m^0$ the optimal length of the muscle, $l_m^{sh}$ the width of the Gaussian force-length curve, $l_m^{min}$ and $l_m^{max}$ the minimal and maximal length of the muscle. $L_m^{opt}$ the relative optimum muscle length, $L_{sh}$ the relative width of the force-length curve.
In [3] the authors propose a relation that gives the variation of optimal muscle length $l_m^0$ according to the level of activity:

$$l_m^0(t) = l_m^0\left(\gamma(1 - a(t) + 1)\right) \tag{4}$$

where $l_m^0(t)$ is the muscle optimal length at time $t$, $l_{m0}$ the muscle optimal length at full activity ($a(t) = 1$) $\gamma$ is the percentage change in optimal muscle length varying between $10\%$ and $20\%$, chosen equal to $15\%$.
The muscle also generate a passive force which is here neglected (the parallel spring with the contractile element in Fig.1).
According to Fig.1, the length of the tendon can be computed by (5).

$$l_t = l_{mt} - l_m \tag{5}$$

The tendon force $F_t$ can be considered as a lumped elasticity $k_t$. As a point of start it will be considered constant here with the value given in [4]. Despite in [5] and [6] it is considered that the tendon's stiffness is not constant, and that its variation is non-linear.

Finally, considering the mass of the muscle $M_m$ and its viscosity $B_m$, and applying the fundamental dynamic equation to the muscle the following relation giving the muscle length can be obtained:

$$M_m \ddot{l_m} = F_t - F_m - B_m \dot{l_m} \tag{6}$$

## III. Dynamic modelling of the extension-flexion of the elbow joint

This paper focuses on the limb muscles and particularly in the muscles involved in the elbow joint movements. Even if the developed force is lower than for the leg, less muscles are involved than for the knee movements, therefore the anatomy and the modelling are less complex, which has been preferred for a feasibility study.

### A. Anatomy of the elbow joint for flexion-extension

The human elbow joint has three rotational degrees of freedom that allow the hand to move in a wide operational space and to do the pronation and supination movements. Moreover, from here we only the flexion and extension (rotation around $\boldsymbol{z}$ axis) of the elbow joint as shown in Fig.3 will e considered.
The flexion-extension of the elbow joint involves only four muscles:

- the Biceps brachii, the Brachialis and the Brachioradialis for flexion,
- the Triceps brachii for extension.

A first approach has been to consider only the two main antagonist muscles: the Biceps and the Triceps, but the first measurements have shown that it was impossible to restrict the arm to such a model as it is impossible to avoid the work of a muscle involved in a specific movement, here the Brachialis and the Brachioradialis. The four muscles must be considered. It can be possible to consider that the Biceps and the Brachialis are working all together and also to consider that they have the same activation pattern since it is not possible to measure the activity of the Brachialis with surface electrodes. Similar approximations to estimate the activity of deep muscles are commonly used, for example in [3] for the lower limb muscles.

### B. Dynamic equations of the system

The joint dynamics is described by (7).

$$J\ddot{q} = T = T_1 + T_2 + T_3 + T_4 + T_{ext} - B_l\dot{q} \tag{7}$$

where $J$ is the inertia of the moving part of the body (forearm and hand), $q$ is the joint coordinate, $\dot{q}$ and $\ddot{q}$ its first and second derivatives, $T$ is the joint torque, $T_i = F_{ti} r_i$ is the torque due to the musculo-tendon complex $i$, $F_{ti}$ is the

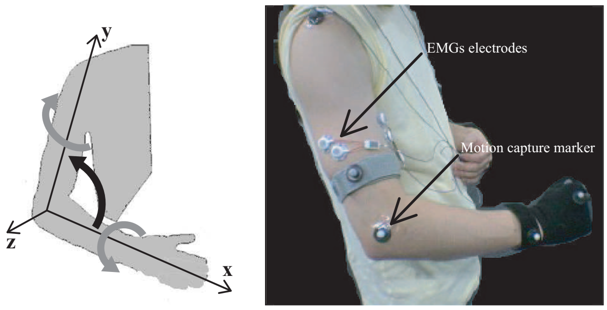


Fig. 2. The elbow joint degrees of freedom

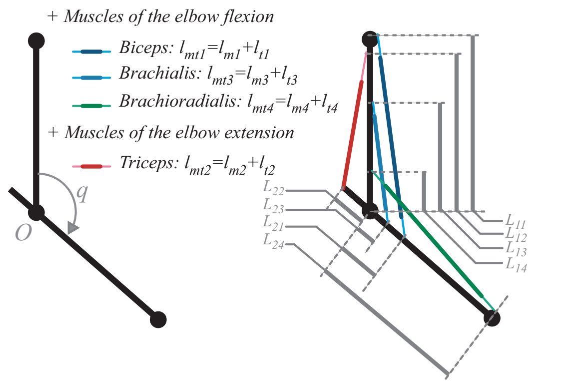


Fig. 3. The elbow joint with its 4 contraction and extension muscles

force applied by tendon $i$, $r_i$ is the moment arm of musculo-tendon $i$ on the moving part, $T_{ext}$ the external torque due to external forces and gravity, and $B_l$ the viscosity of the joint. The moment arm $r_i$ and the length of the musculo-tendon complex $l_{mti}$ are computed using geometric considerations in the triangle (8).

$$l_{mti} = \sqrt{L_{1i}^2 + L_{2i}^2 - 2L_{1i}L_{2i}\cos q} \tag{8}$$

### C. Simulation of the elbow joint dynamics

This model has been used to build a Matlab-Simulink simulator to study the musculo-tendon behavior. Some results are given in Fig. 3 for a flexion-extension movement of the elbow joint with step neural input (see (9)).

## IV. Experimental setup

### A. EMGs recording - Muscle activity

The muscle activation $u(t)$ is recorded using an EMGs (ElectroMyoGraphy) system. This system uses surface electrodes that are fixed on the skin above the muscle. It can only give the activation of the superficial muscles (the one just under the skin): Triceps, Biceps and Brachioradialis. As mentioned above the activity of the Brachialis is supposed to be the same as the activity of the Biceps. To obtain good measurements the skin must be prepared and the temperature

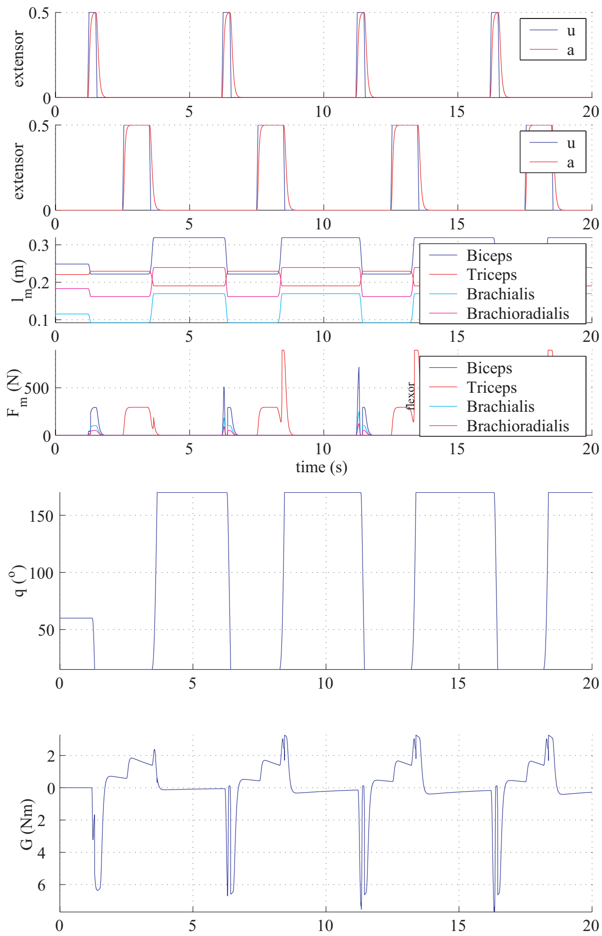


Fig. 4. Simulation of the flexion extension of the elbow joint

and humidity of the room better controlled. Despite those precautions data could have some noise, but it can be efficiently removed by filtering (Fig.5). The filter used is a low pass forward and reverse Butterworth, applied after the full wave rectification of the EMGs such as described in [7].

In the literature several models give the muscle activity $a(t)$ with respect to the muscle activation $u(t)$ using first order differential equation such as [2] and [8] or second order differential equation such as [3] and [9]. The latest, given by (9) is the easiest to use and gives good, smooth results with only three time constants.

$$\begin{aligned} \dot{e} &= (u-e)/\tau_{ne} \\ \dot{a} &= (e-a)/\tau \text{ where } \tau = \begin{cases} \tau_{ac} & e \geq a \\ \tau_{deac} & e < a \end{cases} \end{aligned} \tag{9}$$

where $e$ is an intermediate variable, $\tau_{ne}$ is the excitation time constant, $\tau_{act}$ and the activation and deactivation time constants that are quite all the same for every one since it is based on the kinetics of the chemical reaction of calcium in the muscle. Usually $\tau_{act} = 15\,ms$ and $\tau_{deact} = 50\,ms$,

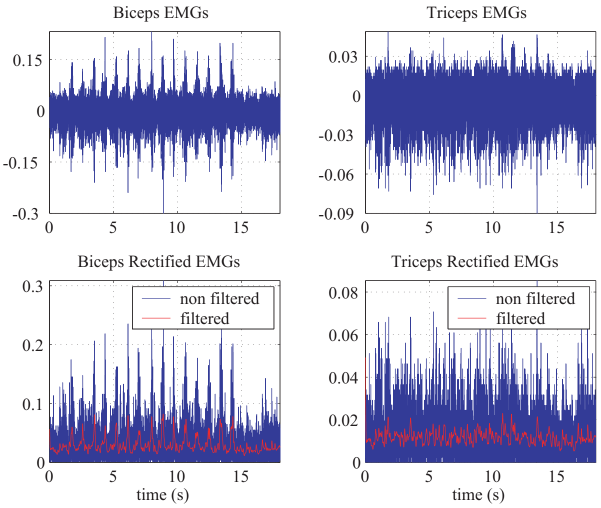


Fig. 5. EMGs, rectified EMGs and filtered rectified EMGs of the Biceps and the Triceps for a flexion/extension of the elbow

however for old people the deactivation time increases to $60ms$ according to [10].
Finally the muscle activity is normalized with respect to the maximum voluntary contraction activity in order to have: $\forall t, 0 \leq a(t) \leq 1$.

### B. Motion capture system - Joint position and torque

The in-house motion capture system is used. The whole system is capable of capturing the marker's position at 30 $fps$ along with the data EMGs data at 1 $KHz$.
Only five markers are necessary (Fig.3) to record the elbow joint movements since the trunk is not moving in the experiments. The inverse kinematics and the inverse dynamics models are computed by a musculo-skeletal model of the human body (Fig.6), using those measurements [11] and the model described in [12]. With the markers position input it gives the joint position $q$ with the inverse kinematics and the joint torque $T$ using the inverses dynamics, as well as an optimized solution for the tendon forces $F_{ti}$.

### C. Exciting movements for the estimation

The movements for the estimation are chosen in order to excite the dynamic parameters that have to be estimated. They also must verify the conditions that ensure the good estimation of the muscle forces such as:

- the tendon must have the smallest solicitation so that $F_{ti} \approx F_{mi}$,
- co-contraction of antagonist muscles must be limited to ensure that the optimal solution found by the optimization procedure is realistic (if co-contraction occurs infinite number of solutions is found)

To ensure this latest condition one solution is to make experiments with movements that have been previously learned

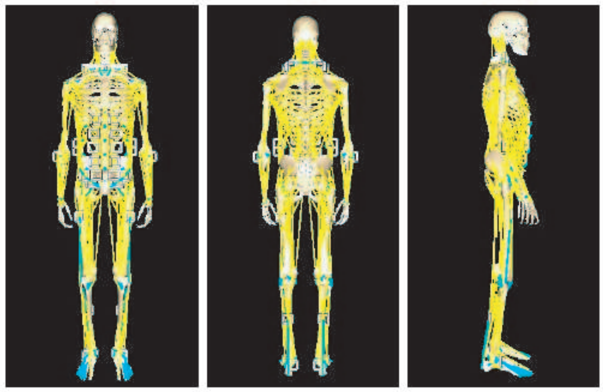

Fig. 6. Musculo-skeletal human model

since it has been shown in [13] that learned movements limit the co-contraction of antagonist muscles. Precise movements (grasping and posing tasks for example) also require a control pattern with co-contraction of the muscles, those movements are avoided. Consequently, in order to have good exciting movements it is to be noted that the parameters for all the muscles cannot be estimated with the proposed method, in the mean time but sequently: degree of freedom by degree of freedom.

## V. IDENTIFICATION OF MUSCULO-TENDON DYNAMICS

### A. Criteria

The estimation is a non linear multi-variable optimization problem. According to the expression of the muscle force the criteria must be separated in three cases depending on the value of the muscle contraction velocity $\dot{l}_m$ (shortening or lengthening) and also with respect to $v_{max}$. Cases when the muscle is not activated ($a_i = 0$) are excluded as they mean that the muscle is therefore not lengthening or shortening. Thus, the two following criteria remain:

- if shortening $-v_{max} < \dot{l}_m < 0$ then:

$$c_1 = \frac{F}{aF_{max}} - exp\left(-\left(\frac{l_m - p_{11}}{p_{12}}\right)^2\right)\frac{p_{13}(v_{max} + \dot{l}_m)}{p_{13}v_{max} - \dot{l}_m} \tag{10}$$

- if lengthening $\dot{l}_m > 0$ then:

$$c_2 = \frac{F}{aF_{max}} - exp\left(-\left(\frac{l_m - p_{21}}{p_{22}}\right)^2\right)\frac{p_{23}v_{max} + p_{24}\dot{l}_m}{p_{23}v_{max} + \dot{l}_m} \tag{11}$$

where $\mathbf{p_1} = [p_{11}\ p_{12}\ p_{13}] = [l^0_{mi}\ l^{sh}_{mi}\ V_{shi}\ ]$ is the vector of parameters to estimate with criterium $c_1$ and $\mathbf{p_2} = [p_{21}\ p_{22}\ p_{23}\ p_{24}] = [l^0_{mi}\ l^{sh}_{mi}\ V_{shi}V_{shli}\ V_{mli}]$ the vector of parameters to estimate with criterium $c_2$.
In order to solve this problem with non linear multi-variable optimization technics based on simple Matlab functions *fminsearch* function is used. In order also to take into account the

over-determinate property of the system the chosen criteria is finally:

$$C_i = \sum_{k=1}^{n_i} \frac{c_i(k)^2}{n_i} \tag{12}$$

where $i$ corresponds to the case according (10) and (11) and $n_i$ is the number of sample available for this criterion, with $n_1 + n_2 \leq n_s$ where $n_s$ represents the total number of samples of the considered movements.

### B. Experimental results

The muscle activity for the Triceps, the Biceps (assumed to be the same for the Brachialis) and the Brachioradialis is measured, rectified and filtered. The joint position is computed using the inverse kinematics as mentioned in the previous section and the joint torque and the musculo-tendon forces are also computed. The movements for the estimation are chosen so that the flexor and the extensor muscles are working separately and are activated enough to develop a significant force that guaranty the identifiability of the parameters. They are achieved in the horizontal plan so that the effect of gravity are limited. Results are then given for the Triceps, the Brachialis (grouped with the Biceps) and the Brachioradialis. The maximal isometric force $F_{max}$ is given in the literature for the upper limb [9] for a maximal activation. Eq.(4) is used to give the variation of this force according the activity level. The initial values of the parameters of $\mathbf{p_{i_{init}}}$ are the approximative value that can be found in [9].

Preliminary results are given in tables I and II according the case, for the Triceps, the Brachialis (grouped with the Biceps) and the Brachioradialis .

TABLE I

ESTIMATED PARAMETERS WITH $C_1$

| parameter | $l_{m0i}$ $p_{11}$ | $l_{mshi}$ $p_{12}$ | $V_{shi}$ $p_{13}$ |
|---|---|---|---|
| $\mathbf{p_{2_{init}}}$ | 0.215 | 0.0176 | 0.3 |
| $\hat{\mathbf{p}}_2$ *Triceps* | 0.224 | 0.001 | 0.409 |
| $\mathbf{p_{3_{init}}}$ | 0.142 | 0.035 | 0.3 |
| $\hat{\mathbf{p}}_3$ *Brachialis* | 0.124 | 0.019 | 0.374 |
| $\mathbf{p_{4_{init}}}$ | 0.212 | 0.035 | 0.3 |
| $\hat{\mathbf{p}}_4$ *Brachioradialis* | 0.1905 | 0.0313 | 0.3594 |

TABLE II

ESTIMATED PARAMETERS WITH $C_2$

| parameter | $l_{m0i}$ $p_{21}$ | $l_{mshi}$ $p_{22}$ | $V_{shi}V_{shli}$ $p_{23}$ | $V_{mli}$ $p_{24}$ |
|---|---|---|---|---|
| $\mathbf{p_{2_{init}}}$ | 0.215 | 0.0176 | 0.1200 | 1.3000 |
| $\hat{\mathbf{p}}_2$ *Triceps* | 0.171 | 0.0181 | 0.1351 | 1.3760 |
| $\mathbf{p_{3_{init}}}$ | 0.142 | 0.035 | 0.12 | 1.3 |
| $\hat{\mathbf{p}}_3$ *Brachialis* | 0.124 | 0.0189 | 0.2622 | 0.6315 |
| $\mathbf{p_{4_{init}}}$ | 0.212 | 0.035 | 0.12 | 1.3 |
| $\hat{\mathbf{p}}_4$ *Brachioradialis* | 0.170 | 0.025 | 0.171 | 0.174 |

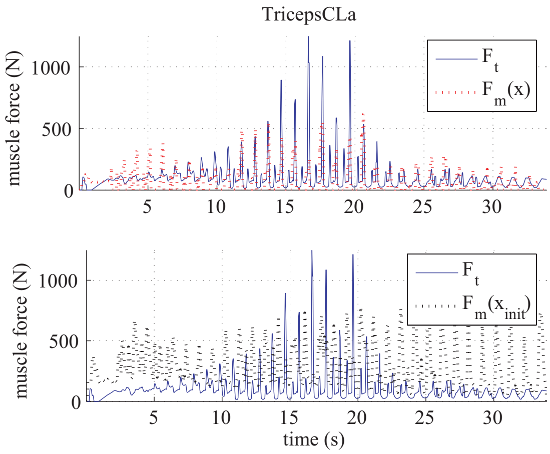


Fig. 7. Comparison with the muscle force computed with musculo-skeletal model and with the muscle model, for the Triceps

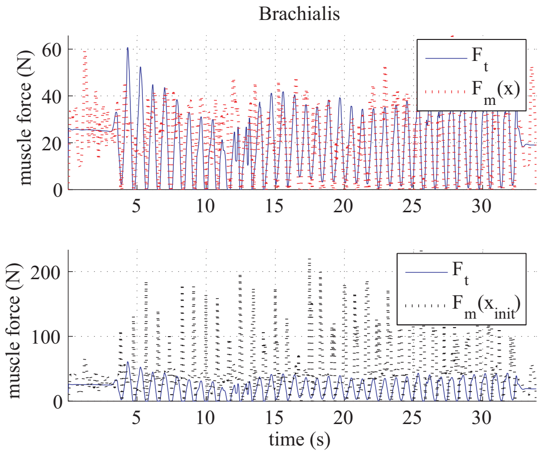


Fig. 8. Comparison with the muscle force computed with musculo-skeletal model and with the muscle model, for the Brachialis

### C. Interpretation and discussion

The results given here in 7, 8 and 9 show that the estimation can be considered as successful. Efforts fit quite well. The muscle forces computed with the estimated parameters (red line) and the ones computed by optimization of the inverse dynamics (blue line) are much more alike than the ones computed with the parameters found in the literature (dot black line), based on average parameters. Parameters estimated with case 1 (resp. case 2) $p_{11}$ and $p_{21}$, (resp. $p_{12}$ and $p_{22}$) that represent the same physical value are the same for each case which shows a certain correctness in the model (ie. in the value of $v_{maxi}$).

Despite, those results need improvement. The model is rather simple and does not take into account the full dynamics of the system: passive force, pinnation angle... This step only treats the problem of muscle parameters, although the tendon slack length $l_{t0}$ is very influent in the musculo-tendon

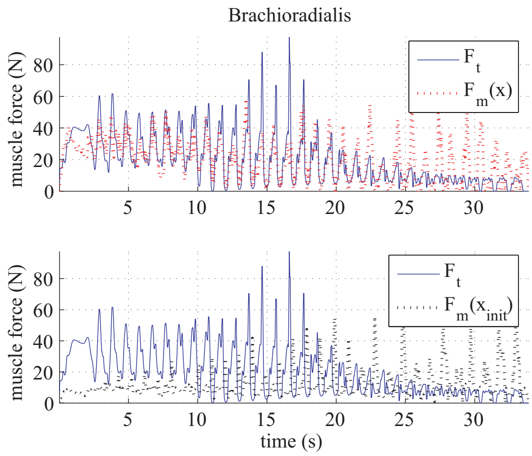


Fig. 9. Comparison with the muscle force computed with musculo-skeletal model and with the muscle model, for the Brachioradialis

dynamics. Conditions and assumptions of the tests: $F_{ti} \approx F_{mi}$ is restrictive and difficult to check. The maximal isometric force $F_{maxi}$ has been taken from the literature and not scaled to the subject. The choice of the optimization technique can also be discussed.
Further works plan to consider all those remarks by enhancement of the model and the optimization technique. However those works show the feasibility of the subject calibration of the musculo-skeletal model used for the computation of the human body dynamics.

## VI. Conclusion

These preliminary experimental results have shown that even a very simple model of musculo-tendon complex allow to reconstruct the muscle forces after estimating the musculo-tendon parameters. Contrarily to usual literature in this field the Hill-based model parameters are estimated, and not only some global parameters with little physiological meaning. It shows that it is possible to estimate the muscle dynamics using EMGs data and motion capture system with quite simple tasks. Once the parameters estimated, it will be possible to add the muscle model to the musculo-skeletal dynamic model used for the computation of the inverse kinematics and inverse dynamics and thus to improve the results of the computed muscle force. Such results allow to improve the knowledge of the human dynamics and of the muscle constraints for example during some specific movements of sports. It is very promising to apply such a method to people who have suffered injury to check their recovery, or to people with muscle disease. Improvements in the model will soon be done to fit more easily with the subject and to be more physiologically correct. Those results are very important in the knowledge of the human body dynamics as well as for the modelling and design of human robots biologically inspired using artificial muscles, as in medical applications such as sport science, rehabilitation, muscle diseases as they allow to understand, more precisely simulate and control the muscle dynamics not from averaged data measured on a population of well chosen subjects but with subject specific parameters.


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