Motion Analysis of the Arm Based on Functional Anatomy

Charles Pontonnier[1] and Georges Dumont[1,2]

[1] IRISA/BUNRAKU,
Campus de Beaulieu,
F-35042 Rennes Cdex, France
[2] ENS Cachan Antenne de Bretagne,
Campus de Ker Lann,
F-35170 Bruz, France

Abstract. This article presents a biomechanical model of the right arm, developped with respect to the functional anatomy of the human. This model is developped as a motion analysis tool. The main application issued from this model is the muscle forces estimation of the flexion/extension and internal rotation of the forearm joints. This estimation is based on an inverse dynamics method, improved with additionnal constraints such as co-contraction factor between flexors and extensors of a joint. The article first presents the related work, then presents the biomechanical model developed, and at last some results obtained for a sample movement of the arm.

1 Introduction

The proper design of working stations has a direct impact on the working conditions. Ergonomics takes an important place as a factor of productivity. Indeed, musculoskeletal troubles are often associated with the working stations in the industry, damaging the health of the worker and decreasing the productivity. In France, the increase of musculoskeletal troubles at work is very consequent since the addition of the table 57 in September 1991 into the professional diseases legislation. This table mainly includes the articular troubles, particularly the troubles associated to the upper extremities. These musculosketetal troubles represent 75 percent of the professional diseases in France [1]. The purpose of this article is the presentation of a biomechanical model of the upper extremity that could be usable to decrease the musculoskeletal troubles. One of the solutions to improve the working conditions is to estimate and analyze muscle forces developed by a human during its work tasks. This estimation is a good way to improve the ergonomics [2], because of the tools that can be used to perform the analysis [3]. The analyzing tool presented with the biomechanical model is a muscle forces estimation method.

The reminder of this article is structured as follows : first we present the related work that is the basis of our study. Next we present our biomechanical model and its analysis tool in three steps, as described above. Our results present

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estimated muscle forces involved in flexion/extension and internal rotation of the forearm joints for a captured motion. We discuss about these results with respect to the literatture and others biomechanical models. At last, we conclude on the method and its limits and we present the future fields that we want to explore.

2 Related Work

This section is divided in two parts. First we present several biomechanicals models that present interesting methods and results. We detail the performances of these models in order to show the relevance of the model we have developped. The second part presents several works that are used as a basis for our method of estimation of the muscle forces.

2.1 Biomechanical Models for Motion Analysis

Currently, several biomechanical models are developped around the world. All of them present different advantages and drawbacks, reaching different goals.

Delp and his collaborators have developed an open-source platform named OpenSim [4]. This platform allows the user to develop dynamic simulations on a musculoskeletal system with motion capture data, using an original algorithm (Computed Muscle Control) based on muscles excitations to provide muscle forces. The computation time is very long (10 minutes for 3 seconds of simulation). An upper extremity model developed by Holzbaur and al. in [5] is available on this platform. Figure 1 shows this upper extremity model. The model allows the user to develop motion analysis from motion capture data.

Yamane and al. [6] have designed a complete musculoskeletal system representing human including 366 muscles driving 155 degrees of freedom. It computes muscle forces from motion capture involved in a walk in 1 second per frame, so it can not be used to drive real-time application. It is based on a physiological and physical approach, including an optimisation algorithm.

Chalfoun has developed a simulation toolkit for the forearm and the hand [7]. The musculoskeletal system is very realistic, using a complete muscular topology

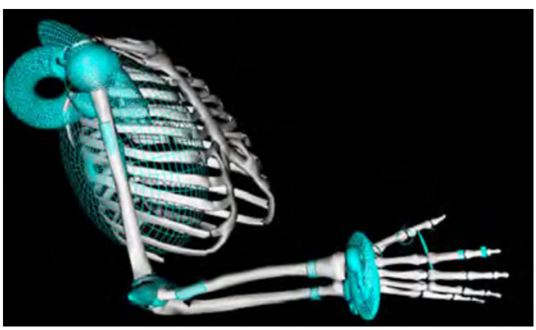


Fig. 1. Upper Extremity model designed with OpenSim [5]

of the hand and the forearm. It provides good results that have been compared to EMG data. This platform does not provide any interactive tool, the motion has to be modelled to obtain any result.

Maurel developed a musculoskeletal model for the shoulder [8]. This model is very realistic and has precise information about muscular topology of the arm and shoulder kinematics. The information about muscular topology are interesting in order to compute muscle moment arms in our estimation.

These musculoskeletal systems have a great interest in our study, and are good support for our work. The main advantage of these models are their realism. The results obtained with OpenSim and the Yamane's model are sufficiently validated to be used as a comparison. Nevertheless, we want to have muscle forces data to apply ergonomic tools on them, so we have to develop a faster and simpler technique, in order to implement it in real time. This is the main drawback of these models, they are too heavy and slow to be used dynamically.

2.2 Muscle Forces Estimation

There are two main approaches for studying muscle forces involved in human motion, the first is the forward dynamics approach and the second is the inverse dynamics approach. Buchanan presented these two methods in detail [9]. This section deals with the advantages and drawbacks of the two methods.

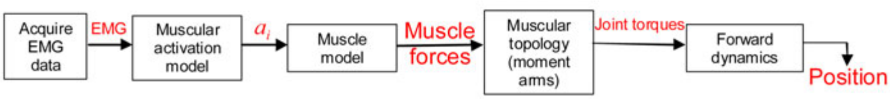


Fig. 2. Forward dynamics approach for estimating muscle forces involved in human motion [9]

Figure 2 presents the forward dynamics method. This method is divided in five different steps. This first step is based on electromyogramms (EMG) data acquisition and is also the main advantage of the forward dynamics method. The second step is the estimation of the muscle force by a muscular activation model that is directly applied muscle by muscle. The lack of knowledge on muscular modeling and muscular parameters [10] is the main limitation of the method (third step). The model has to be fitted in order to estimate muscle forces that are dynamically consistent. Signal processing related to the EMGs treatment constitutes the second limitation. The signal obtained from the electrodes presents various noises (activity of other muscles near the measured muscle), so the signal has to be processed with many arbitrary elements (filters, optimization loops). At last, the instrumentation is quite heavy because of the number of electrodes that should be equal to the number of muscle activities that are to be measured. The fourth and fifth steps are checking steps that allow comparing muscle forces obtained from the forward dynamics method with positions obtained, for example, with motion capture data.

Fig. 3. Inverse dynamics approach for estimating muscle forces involved in human motion [9]

Figure 3 presents the inverse dynamics method for studying human movement. This method is divided in different steps from right to left (these steps are very close to the forward dynamics method steps) . The inverse dynamics method uses kinematics data (such as motion capture data) in order to compute muscle forces by using an inverse dynamics method. The second step is an inverse dynamics step. The main advantage is that muscle forces are issued from mechanical equations end thus are dynamically consistent. The third step is an optimization step.

The first drawback of this method is caused by the redundancy of the muscular topology for each joint. Generally, many muscles are involved in one joint motion, and several muscles are working on two or three different joints. This redundancy implies the use of optimization methods to obtain muscles forces from joint torques data. The redundancy implies another important limitation: the muscle forces issued from the computation do not take into account the muscle co-contraction. Without any information on muscular antagonism, many muscles do not have the activity that they are supposed to have. The method that we propose in this article takes the co-contraction into account by using an additional constraint in the optimization formulation. At last, the inverse dynamics method could be slow because of this optimization step. This problem is an important limitation in a virtual reality approach that implies interaction with a real human and so that has to deal with real-time applications. We propose a solution to this problem in the last part of the article. The fourth and fifth steps are checking steps that allow comparing the estimated muscle force to EMG measures. The instrumentation for the experimentation is mainly a motion capture system that is well adapted to be an input for virtual reality application.

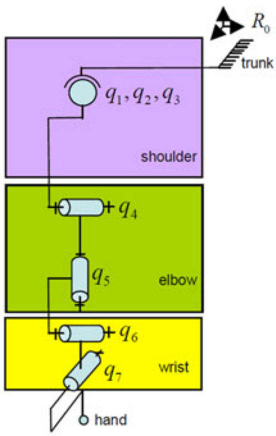
3 Biomechanical Model of the Right Arm

Our model is divided in three distinct parts. In this section we first present the kinematical model we have developed. Next we present the dynamical model developed to obtain joint torques from joint positions, velocities and accelerations issued from the inverse kinematics computation. At last we present the musculoskeletal model and the method developed to estimate muscle forces from the two precedent models.

3.1 Kinematical Model

This kinematical model is based on functional anatomy [11]. Figure 4 presents the model and Table 1 presents the joint limits.

In order to analyse a motion, we use motion capture data (issued from a VICON©system) and an inverse kinematics algorithm that computes the joint positions associated to the motion. The motion capture gives us position data for each segment of the model, we have developed an inverse kinematics method based on a succesive replacement of each segment one by one. We compute the inverse kinematics algorithm for each segment, following the chain segment by segment downward (see Figure 4) from the shoulder to the wrist.



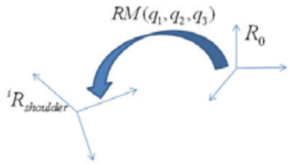
Our study is based on the elbow motion and the following joints in the kinematical chain. We consider the shoulder as a spherical joint. We do not take into account the constitution of the joint; we only use it to place the arm in the good position and orientation. For our range of motion, the spherical approximation is sufficient in order to rebuild the motion. In a further development we may use the Maurel's model [8]. The elbow is modeled as a gimbal joint that allows the flexion/extension and the internal rotation of the forearm. At last, the wrist is represented by two rotations that correspond to the flexion/extension and to the adduction/abduction of the hand.

Fig. 4. Kinematical model of the right arm

Table 1. Joint functions and bounds of the kinematical model of the right arm

Joint	Function	Bounds(°)
q_1	Flexion/Extension of the arm	[0,180]
q_2	Abduction/Adduction of the arm	[-60,90]
q_3	Internal rotation of the arm	[-90,30]
q_4	Flexion/Extension of the forearm	[0,150]
q_5	Internal rotation of the forearm	[0,165]
q_6	Flexion/Extension of the hand	[-80,90]
q_7	Abduction/Adduction of the hand	[-50,20]

To obtain joint positions, we resolve a reduced system of equations issued from the equality between the real orientation matrix computed from markers positions and a combination of the rotation matrix issued from the kinematical model. For example, in order to orient and place the shoulder, we will solve a reduced system decribe below in figure 5. The main advantage of this method is its computation time, which is near 1 ms for one frame treatment.



$$RM(q_1, q_2, q_3) = [rot(\overrightarrow{y_0}, q_1)] * [rot(\overrightarrow{x_1}, q_2)] * [rot(\overrightarrow{z_2}, q_3)]$$
$$^{i}R_{shoulder} = [^{i}\overrightarrow{x}_{shoulder}, {}^{i}\overrightarrow{y}_{shoulder}, {}^{i}\overrightarrow{z}_{shoulder}]$$
$$RM(q_1, q_2, q_3) = {}^{i}R_{shoulder}$$

Fig. 5. Definition of orientation of the shoulder for the frame i, where $RM(q_1, q_2, q_3)$ is the rotation matrix issued from the combination of the rotation angles q_1,q_2 and q_3 defined above. $^{i}\overrightarrow{x}_{shoulder}$,$^{i}\overrightarrow{y}_{shoulder}$ and $^{i}\overrightarrow{z}_{shoulder}$ are the three vectors constituting the direct orthonormal basis associated to the shoulder for the frame i.

The results obtained with this method allow us to compare the position of the reconstructed markers and the position of the real markers issued from the motion capture data. The main error is near 1%, which represent in our application a maximal distance between real and reconstructed markers near from 1,5 mm.

3.2 Dynamical Model

The dynamical model that we have developed is realized by using the Matlab© Simmechanics toolbox. The right arm is modelled as an articulated system of rigid bodies. The inertia parameters are defined for each motion capture subject with respect to the De Leva tables [12] and are automatically scaled with a precomputing algorithm that we have developed [13]. The rigid bodies are connected with perfect mechanical joints with respect to the kinematical model (figure 4).

This model allows us to compute the joint torques involved in the motion. A numerical derivation is applied to the joint positions obtained from the inverse kinematics step. The simulation applies the Newton laws of dynamics to the system and thus computes the joint torques. These torques are then used to compute the muscle forces.

A visualization of the motion is associated to this model. This model is constructed according to the kinematical model defined in figure 4 and is an assembly of a geometric definition of each segment [14].

3.3 Musculoskeletal Model

The musculoskeletal model is designed in two steps. First we modelize the muscles and attach them to the skeleton. At last we define an optimization algorithm to compute muscle forces.

Muscular Topology and Functional Anatomy: To obtain a fine analysis of the forces developed by the muscles during the motion, we have to properly define their topological situation on the target skeleton, their role (in which functional joint of the arm they are involved) in the motion, and at last their properties and capabilities. We have chosen to define the muscles as viscoelastic actuators.

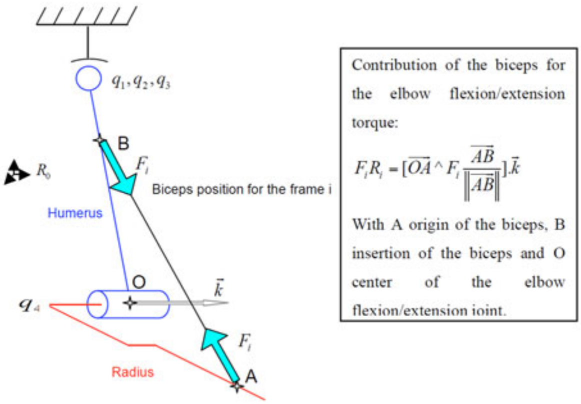


Fig. 6. Computation of the contribution of the biceps for the elbow flexion/extension torque

This approach is commonly accepted in the biomechanical community. We can cite for example the work of Zajac [10]. This model is useful to define the cost function to minimize and the constraints associated that allow us to estimate muscle forces, as it is described further.

At each frame we rebuild the muscle origins and insertions in the main coordinate system to obtain the moment arms related to each joint. Figure 6 shows how the contribution of the biceps is computed for the flexion/extension of the elbow motion. The muscle is considered as a mechanical actuator and the force developed by the muscle is oriented in the main direction of the muscle. Furthermore, muscles work only in contraction. The origins and insertions of the muscles are defined on the basis of Clinically Oriented Anatomy [11]. We use the topological information issued from this book to define our own origins and insertions with respect to the dimensions of the target skeleton. The origins and insertions are scaled on the basis of the humerus and radius length. Our model does not provide any warping point or via point in the muscle action lines, such as in Holzbaur's work [5], so that could be a further improvement if our results are not sufficient with the actual definition of the muscles. The computation of the muscle moment arms leads to the definition of equilibrium constraints between the computed torques issued from the inverse dynamics step and the muscle contribution for each joint, as it is described in the next section.

Table 2 summarizes the adimensonal coordinates of the muscles involved in the flexion/extension and the internal rotation of the forearm. Muscles with multiple origins and insertions are modeled with only one origin and one insertion. In order to use ergonomics tools [3], we only define one force for one muscle.

Muscle Forces Estimation: As previously mentioned, the estimation of muscle forces with an inverse dynamics method is a redundant problem. The equilibirum of one joint leads only to one equation for many muscle forces. These equations express that the torques obtained from the inverse dynamics are equal

Table 2. Adimensional origins and insertions of muscles

Muscle	Origin (adimensional)	Insertion (adimensional)
Biceps	$[-0.085\ -0.043\ 0.043]_{^iR_{shoulder}}$	$[-0.045\ 0.045\ -0.099]_{^iR_{elbow}}$
Triceps	$[0.043\ -0.021\ 0.128]_{^iR_{shoulder}}$	$[0.062\ 0\ -0.037]_{^iR_{elbow}}$
Brachialis	$[-0.037\ 0\ -0.531]_{^iR_{shoulder}}$	$[-0.05\ -0.025\ -0.124]_{^iR_{elbow}}$
Brachioradialis	$[-0.043\ 0\ -0.798]_{^iR_{shoulder}}$	$[0\ -0.099\ -0.943]_{^iR_{elbow}}$
Anconeus	$[0.043\ 0.085\ -0.957]_{^iR_{shoulder}}$	$[0.037\ 0.025\ -0.124]_{^iR_{elbow}}$
Pronator teres	$[0.043\ 0.106\ -0.957]_{^iR_{shoulder}}$	$[0.05\ 0.025\ -0.298]_{^iR_{elbow}}$
Pronator quadratus	$[0.037\ 0.05\ -0.868]_{^iR_{elbow}}$	$[0.037\ -0.074\ -0.868]_{^iR_{elbow}}$
Supinator	$[-0.198\ 0\ 0.05]_{^iR_{elbow}}$	$[0\ 0.099\ -0.55]_{^iR_{elbow}}$

to the sum of the contributions of each muscle related to the joint. The most common and natural solution to this problem is to minimize a cost function under non-linear constraints that represents the equilibrium equations, the physiological limits and functions of the muscles and the muscular topology of the arm. Our work is mainly focused on the design of these constraints, whose have to be chosen and developed to perform the most realistic muscle forces estimation.

The choice of the cost function is not obvious. Several works are studying different cost functions to estimate realistic muscle forces. The main work that we have used to make our choice is Challis' work [15]. The chosen cost function is the normalized sum of the squared muscle stresses. This choice is strongly related to the hypothesis that biomechanical energy is minimized for the human movements. We associate constraints to the cost function in order to represent the physiology of the muscles. Equation 1 shows the chosen cost function to minimize.

$$f = \sum_{m} \left(\frac{F_i}{(F_{\max})_i} \right)^2 \tag{1}$$

In which F_i is the force applied by muscle i and $(F_{max})_i$ is the maximum isometric force developed by the same muscle. As we proposed in [16], the maximum isometric force developed by a muscle depends on the joint configuration. The work of Von Konsky [17] allows us to adjust these capabilities for the muscle involved in the flexion/extension of the forearm for each frame. The lack of knowledge about maximum capability of the muscles involved in the internal rotation of the forearm obliges us to consider a constant maximum capability for these muscles, as it is proposed in [5].

Physiologically, the muscles are activated by pair (or pair of muscle groups). In the case of an elbow flexion/extension, when the flexors (Biceps, Brachialis and Brachioradialis) are activated, the extensors (Triceps and Anconeus) are activated too because of the antagonism of the joint. To express this co-contraction phenomenon, we use an additional equality constraint:

$$h_3(F_i) = F_1 + F_3 + F_4 - \alpha_{q_4}[F_2 + F_5] = 0 \tag{2}$$

In which F_1,F_3,F_4 are respectively the forces relative to the Biceps, the Brachialis and the Brachioradialis,F_2 and F_5 are respectively the force relative to the

Triceps and the Anconeus. $\alpha(q_4)$ is the co-contraction factor for the elbow flexion/extension that is issued from an experimentation computed with OpenSim. This first study is a simple treatment of a captured extension of the elbow. We obtain a ratio between the flexors activities and the extensors activities. We name this ratio the co-contraction factor. Co-contraction factor depends on the position of the flexion/extension joint. We use OpenSim as a reference to develop this co-contraction factor. The interest of this co-contraction factor has already been discussed in a precedent article [18]. This article presents the results obtained with and without the co-contraction factor for the elbow flexion/extension. The main goal of this additional constraint is to translate the muscle behavior contained in a complete simulator like OpenSim, without any physiological behavior computation.

At last, we add the equalities constraints that represent the equilibrium between the contribution of each muscle involved in each motion and the corresponding torque issued from inverse dynamics computation :

$$h(F_i) = c - M_c * F = 0 \tag{3}$$

In which c is the vector of the computed joint torques (issued from the inverse dynamics computation), M_c is the contribution matrix, including the moment arms computed at each frame as described in the last section, and F the vector of the muscle forces.

At last the optimization problem could be summarized as follows :

$$\begin{aligned} &\text{For each frame :} \\ \min f(F) &= \sum_m \left(\frac{F_i}{(F_{\max})_i} \right)^2 . \\ &\text{Under constraints :} \\ h_{1,2}(F) &= c - M_c * F = 0 \ . \\ h_3(F) &= F_1 + F_3 + F_4 - \alpha_{q_4}[F_2 + F_5] = 0 \ . \\ h_4(F) &= F_6 + F_7 - \alpha_{q_5} F_8 = 0 \ . \\ g_i(F_i) &= F_i - (F_{\max})_i \leq 0 \ . \end{aligned} \tag{4}$$

4 Results and Discussion

In this section we present some results obtained with the model for a sample movement of the forearm.

Figure 7 presents the joint positions and torques issued from the kinematical and dynamical models. The considered joints are the flexion/extension and the internal rotation of the forearm. The sample movement is simple. The flexion/extension joint presents an angle between 40° and 10° (0° corresponds to a complete extension of the forearm) and the computed torque varies between 0 and 4 newton meters. Those results show that the joint torque is pretty weak during the motion. Actually, the subject does not hold any additional load (use a tool, hold a box). For the internal rotation, the variation of the angle is quite null (only four degrees) and the computed torque is about 1.10^{-3} N.m. This is due to the fact that this joint only holds the distribued loads of the forearm.

Figures 8 and 9 show the estimated forces for the muscles involved in the two joints during the movement. The muscles present an activity that is related to their order of importance. For example, the flexors of the forearm (Biceps, Brachialis, Brachioradialis) are working during the motion, and the main flexor (Brachialis) presents the main activity. The forces obtained are contained in a range of values that are realistic if we consider the joint torques associated. We can see that the co-contraction factor allows the system to compute a related activity of the extensors (Triceps, Anconeus). In the case of the anconeus, it does not represent a big activity. It is due to its minor role in the joint motion. The main limitation of these results is the lack of continuity of the computed muscle forces. Actually, the muscles are considered as viscoelastic actuators, and we have to define some additional rules in the computation in order to take it into account. The first improvement we can add to the algorithm is to obtain a better co-contraction factor. Currently the co-contraction factor is related to the joint position. Our idea is to obtain a law relying it to the joint velocity too. This improvement should allow us to improve the realism of the computed forces.

The lack of validation for these results is the most important step we have to complete in our next work. The results presented here needs to be at least compared with OpenSim results. We are currently working on OpenSim in order to obtain comparative results. We want to ensure that the addition of the co-contraction factor leads to a global behavior of the musculoskeletal system that provides accurate results for the muscle forces estimation. At last, we are currently recording some new motion data in order to improve the global results (co-contraction factor definition) and see different working cases.

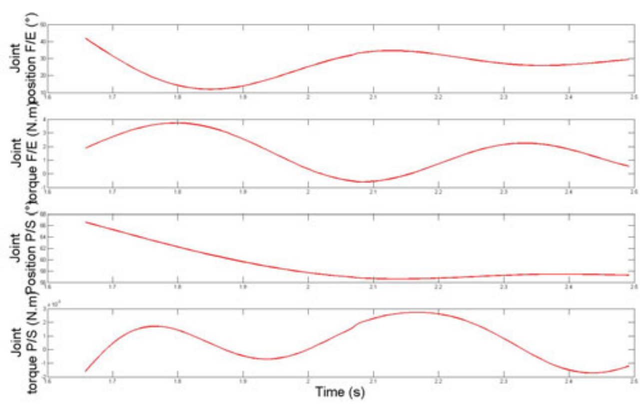


Fig. 7. Inverse dynamics results for a sample movement of the forearm

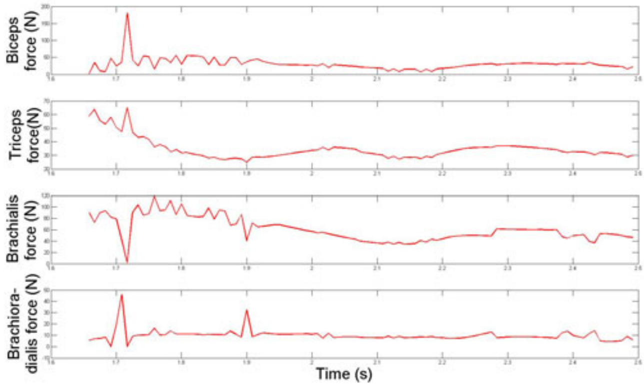


Fig. 8. Estimated muscle forces for a sample movement of the forearm

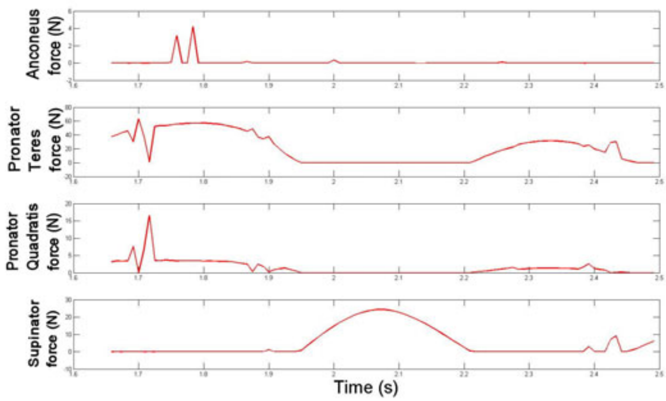


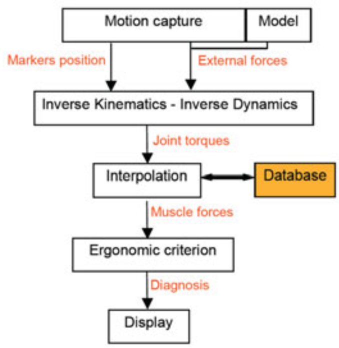
Fig. 9. Estimated muscle forces for a sample movement of the forearm

The mean computation time for a frame is 0.04 second, computed on a Pentium IV dual core 2,3GHz processor. This result corresponds to a frequency of analysis about 25 Hz. This is a good result compared to the literatture but it is not sufficient for real-time application.

5 Conclusion and Perspectives

This article presents a biomechanical model of the right arm designed in order to analyse motion for working station design. We have detailed the different parts of the model. The model presents a kinematical part, a dynamical part and at last a biomechanical part. The model is based on functional anatomy. We present some results for a sample motion of the right arm. The analysis of the flexion/extension and internal rotation of the forearm joint is the basis of the discussion about the model.Our results of muscle forces estimation are realistic, but the method presents a lack of continuity that does not correspond to the viscoelastic model [10] that is commonly accepted for the muscles. We have to improve the method to improve the results. The forces obtained are comparable to the ones presented in the litterature, but need further validation (comparison with OpenSim's results, EMG data).

At last, once the method improved, we will replace the optimization step with an interpolation step (see figure 10), that presents better characteristics in terms of computation time. This is the next step in our work.



To use the method in VR sessions, we have to reach 100 Hz for the I/O computation. The main improvement we consider is to interpolate the muscle forces instead of optimizing them online. Our work now is to compute a pool of results in order to constitute a database of muscle forces. This database, computed offline, will allow us to interpolate the muscle forces in online applications. Interpolation does not take much time to compute, so we think that we can decrease the computation time by four with this improvement of the method.

Fig. 10. Real-time application architecture

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