Forces Estimation by Penalised Lagrangian Method For Virtual and Biological Applications

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***Abstract*—This paper deals with development of a highly realistic human hand and forearm model (HHF). The adopted model has to be as close as possible to the reality of the human being hand, to address several features linked to manipulation tasks, grasping objects and daily routine movements like shaving, writing, etc. In addition, thanks to this model, a better comprehension of the biomechanical and neuromuscular behavior of the system is aimed. This will allow, within the framework of the handicap, to have a tool for the simulation of repairing surgery, acts such as tendon transfer. The assistance with the development of prosthesis constitutes a later objective of our simulator. Also, in order to be realistic, the simulation of the movement is made in real –time; meaning, at the same rate as the natural HHF movement. In this paper, we focus on the muscles forces determination for a given task. A relation between the muscles forces and the joints torques is established. The resulting forces, responsible of a dynamical movement of the HHF, are calculated by using an optimization method. The calculation is made during a real-time simulation. The results are discussed and interpreted on examples simulating basic movements of the HHF. Limitations and further developments of the model are discussed.**

Keywords- real-time simulation; muscle forces prediction; optimization; dynamic calculation.

I. Introduction

Proper understanding of the human hand motion is a very challenging task. Knowledge of muscle forces and their action on the body is fundamental for improving the diagnosis and treatment of persons with movement disabilities. This research will be useful for the design of robotic hand similar to the human one. The objective of this study is to reproduce, as close as possible to the reality, the movement of the "Human Hand and Forearm" (HHF) system. In order to have a realistic simulation of an anthropomorphic hand, an accurate study of the anatomy of the HHF system is necessary [1-2]. Knowing the muscles responsible for the HHF movement and the force they develop is the task accomplished in this study.

The muscles are the motor part of the system, a relation between the forces generated in the tendons and the movement of the hand has to be established. This relation should take into account the real anatomical parameters of the HHF system whenever this is possible. Many studies were done in this subject, for instance, the one presented by E.Y. Chao [3] predicts the forces in the normal and abnormal hand during isometric hand function, mainly during the pinch position. Another, presented by V.M. Zatsiorsky [4], studies the force and torques production in static multifinger prehension. E.Y. Chao [3] developed a three-dimensional force analysis of finger joints in selected isometric hand functions for the pinch task. Nevertheless, all these studies were done in static mode where no movement of the joints is produced. In this paper the dynamic movement of the HHF system is taken into account. The estimation of the forces is made, on line, during the movement of the hand.

The first section of the paper gives a brief description of the anatomy of the HHF parts. The system dynamic model, as well as the different parts that form the dynamic equation will be presented. After that, the forward model and the inverse model are formulated. The forward model is used to validate the relation between the muscle forces and the joints toques. The inverse model permits to predict the forces in the hand during the movement. The inverse model is an indeterminate problem due to actuation redundancy. Therefore, an optimization technique is adopted in order to calculate theses forces. The results obtained are validated by comparing two elementary movements of the hand. These movements are the opening and closing of the hand and the pinch movement. Finally, further developments of the model are discussed.

II. Anatomy and assumptions

A. Anatomy

Many studies of the anatomy of the human hand were done during the last decade. C. Eaton [1] developed an anatomical study for each muscle in the HHF system starting from the properties of each muscle in the hand; its functionality and its effect on the joints. Numerical values of the insertion point of each muscle and the maximum force developed are given by A. Sereig [2].

The osseous elements of the human hand and the joints are represented in the fig. 1. [2]. Common extensor of the fingers, as well as two common flexors begin on the proximal surfaces of the forearm. The tendon of the common extensor (extensor digitorium communis, EDC) branches into four tendons on the level of the wrist joint. Each of them going to its own finger and attaching to the middle and distal phalanx. Two common flexors, the common surface flexor (flexor digitorium superficialis, FDS) and common deep flexor (flexor digitorium profundus, FDP) have the same structure: FDS is attached to the middle phalanx and FDP to the distal phalanx.

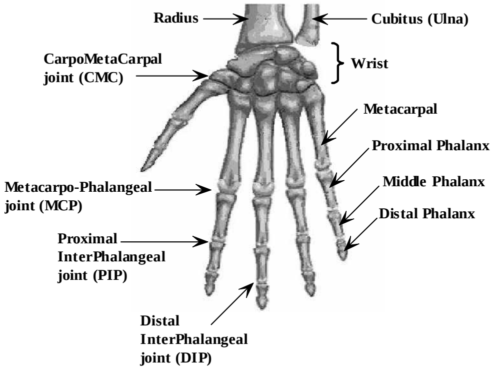

Figure 1 : Osseous members and joints of the HHF [1]

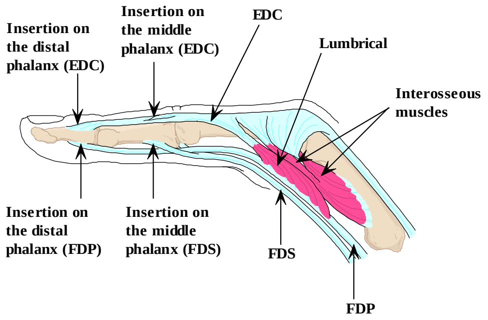

Figure 2: Extensor, flexors and interosseous muscles [2]

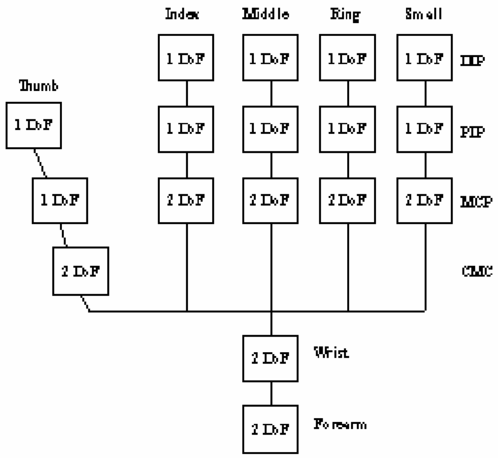

Figure 3: Degrees of freedom

The index has its own extensor muscle (extensor indicis, EI), the small finger has its own extensor muscle (extensor digiti minimi, EDM) and its own flexor (flexor digiti minimi, FDM) and its own abductor (abductor digiti minimi, ADM). The particularity of the extrinsic muscles is that all of them are multi-joint muscles. Compared to other fingers the thumb is quite independent from the point of view of muscle apparatus functioning. Its extrinsic apparatus consists in four muscles: long flexor (flexor pollicis longus, FPL), long and short extensors (extensor pollicis longus, EPL and the extensor pollicis brevis, EPB) and the abductor (abductor pollicis longus, APL). The thumb has also four own intrinsic muscles: the short abductor (abductor pollocis brevis, APB) the short flexor (flexor pollicis brevis, FPB), muscle opposing the thumb (opponens pollicis, OP), and the adductor of the thumb (adductor pollicis, ADP).

Muscles of the hand set in motion numerous hand joints. There are 24 degrees of freedom (dofs) in the HHF system that are split as follows: two dofs in the forearm (flexion/extension and pronation/supination), two dofs in the wrist joint (flexion/extension and abduction/adduction), two dofs in the carpo-metacarpal joint of the thumb, two dofs in the metacarpo-phalangeal joints of each finger (flexion/extension and abduction/adduction), and one dofs in each interphalangeal joint (flexion/extension). This leads to a system of 24 dofs, depicted on Fig.3.

B. Assumptions

Several assumptions had to be made before proceeding to the muscle forces estimation. These assumptions are stated below:

- The tendons are considered as inextensible wires.
- All muscle fibers are oriented in the direction of the tendon. Thus, all muscles are considered not to be pennated ($\alpha = 0$) [5].
- The lumbricals muscles won’t be modeled, due to their structure’s complexity. In deed, they are attached on other tendons and not on the bones.
- Each bone of the HHF has its own coordinate system, as shown in Fig. 4. The insertion point of the tendon, on a bone, will be located according to the reference frame of that bone. The transformation from a coordinate system to another is made by homogeneous transformation matrix. The parameters of these matrices are defined according to the Denavit-Hartenberg description [6]. The Z axe will indicate the rotational axe of the joints depending on the movement of the bone, for example the Z axe of the pronation/supination movement of the forearm joint is parallel to the central axe of the cubitus.
- Any muscle which has an insertion on the phalanx will influence all the joints that its tendon passes by [7].

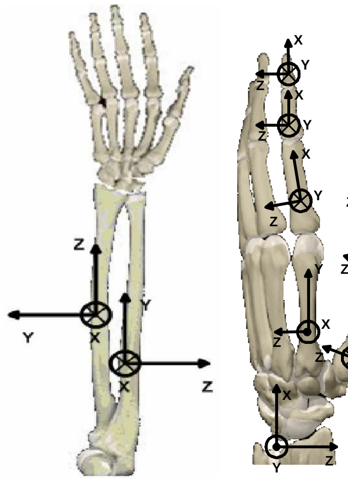

Figure 4 :Axes of the HHF

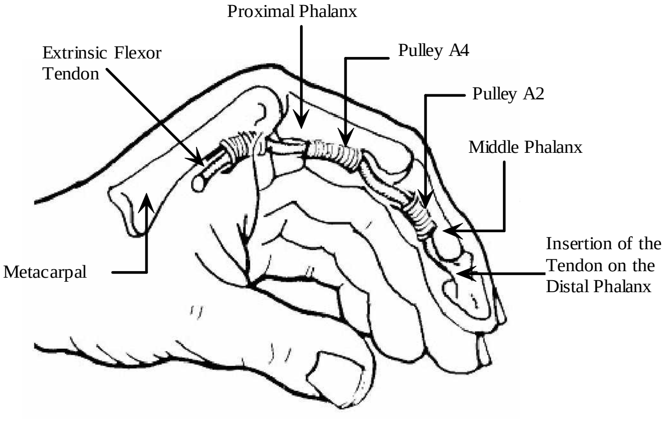

Figure 5 : Pulleys of the index finger [2]

- The extrinsic flexors of the hand that have an insertion on the middle and distal phalanx, like the FDP or FDS pass through cylindrical tissues modeled as pulleys [7]. The movement inside these tissues is made without any friction. There are two pulleys for each finger (see Fig. 5), and one pulley for the thumb.
- Any tendon that has an insertion on the metacarpals will only influence the wrist.

- Any tendon that has an insertion on the ulna will provoke a flexion/extension movement. The pronation/supination is produced by those which are inserted on the radius.
- Recent studies [8] have shown that a single muscle may contain a number of neuromuscular compartments. Each one consists of a separate pool of motor units. These compartments can be differentially activated, indicating that these muscles functionally contain more than one sub-pool. Due to this particularity [8], the two common flexors of the fingers (FDP, FDS) will be subdivided into eight different flexors (one for each finger). This leads us to a system composed of 24 dofs and a total of 45 muscles.

III. System Dynamic Model

The general form of the dynamic equation of the HHF system can be stated as follows [9]:

$$[A(\mathrm{q})]*\left[\frac{d^2q}{dt^2}\right]+[B(\mathrm{q})]*\left[\frac{dq}{dt}\right]^T\left[\frac{dq}{dt}\right]+[C(\mathrm{q})]=[T_{lt}][F_t]+[T_e][F_e] \qquad (1)$$

On the left side of this equation, A is the generalized mass matrix, B represents the Coriolis and centrifugal terms and C concerns the gravity effect. These three entities depend on the angular position (q) of the joints. The vector (q) represents the generalized coordinates as defined on figure 6. Hence, this vector determines the configuration of the human hand in three-dimensional space. $\left[\frac{d^2q}{dt^2}\right]$ and $\left[\frac{dq}{dt}\right]$ indicate the joint acceleration, and velocity.

The right side of this equation represents the torques applied on the system which could be divided into two kinds: those resulting from the muscles of the hand $[F_t]$ (the internal forces) and those produced by the interaction forces $[F_e]$ with the grasped objects. This paper focuses on the calculation of the internal forces produced by the muscles of the hand. These forces are related to the joints torques by the following relation:

$$[T_{lt}]\cdot[F_t]=[\tau] \qquad (2)$$

Where $[F_t]$ is the vector of the tendons forces (45 columns), $[\tau]$ is the vector of the joints torques (24 columns) and $[T_{lt}]$ is the matrix (24 x 45) which elements are proportional to a distance (the calculation and developments of these elements are given below).

A. Forward Model

In the forward model the unknown variables are the joints torques that are computed from a giving vector of forces in the hand. These joints torques can be computed by using equation (2), where F is the desired vector forces in the HHF.

The lines of the matrix $[T_{lt}]$ represent the dofs of the system (total number of 24) and the columns represent the forces in the HHF system (total number of 45 muscles).

Consider the following example with two successive bones, (fig.6). Each bone has two insertion points, (A_1, A_2) and (B_1, B_2). On the first bone, the two tendons will exert the forces F_1 and F_2 respectively. These forces will create a moment M_1 at the rotational center O_1 of the joint. The projection of this moment over the axe of rotation Z_1 (see fig. 7) of the first bone will give the following torque equation:

$$\mathrm{M}_1 = O_1A_1 \times \sin(\overrightarrow{A_1O_1}, \overrightarrow{F_1}) \times F_1 \times \cos(\overrightarrow{Z_1}, \overrightarrow{A_1O_1} \otimes \overrightarrow{F_1}) + O_1A_2 \times \sin(\overrightarrow{A_2O_1}, \overrightarrow{F_2}) \times F_2 \times \cos(\overrightarrow{Z_1}, \overrightarrow{A_2O_1} \otimes \overrightarrow{F_2}) \qquad (3)$$

Where $\otimes$ is the vector cross product operator.

The two forces F_3 and F_4 will create a moment at O_2. The forces F_1 and F_2 will also affect the second joint (assumption 5) by creating an additional moment at O_2.

The resulting equations may be written into a matrix form like follows:

$$\begin{bmatrix} M_{O_1} \\ M_{O_2} \end{bmatrix} = \begin{pmatrix} T_{11} & T_{12} & 0 & 0 \\ T_{21} & T_{22} & T_{23} & T_{24} \end{pmatrix} \cdot \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} \qquad (4)$$

Where for example:

$$T_{11} = O_1A_1 \times \sin(\overrightarrow{A_1O_1}, \overrightarrow{F_1}) \times \cos(\overrightarrow{Z_1}, \overrightarrow{A_1O_1} \otimes \overrightarrow{F_1}) \qquad T_{21} = O_2A_1 \times \sin(\overrightarrow{A_1O_2}, \overrightarrow{F_1}) \times \cos(\overrightarrow{Z_2}, \overrightarrow{A_1O_2} \otimes \overrightarrow{F_1})$$

O_1A_1 is known (assumption 4). To calculate O_2A_1, one needs to express the insertion points in the coordinate system of the second bone. Homogeneous transformation matrices (4x4) $TM_{2\text{-}1}$ are used [10]. Thus:

$$O_2A_1 = TM_{2\text{-}1} \cdot O_1A_1 \quad \text{with} \quad O_iA_j = [X_{O_iA_j} \quad Y_{O_iA_j} \quad Z_{O_iA_j} \quad 1] \qquad (5)$$

The calculation done on the entire system will generate the complete $[T_{lt}]$ matrix.

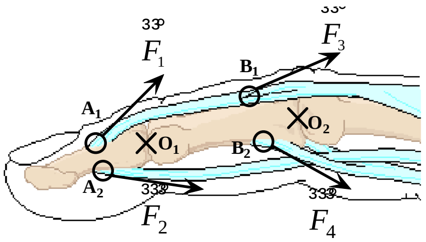

Figure 6 : Forces application's synoptic

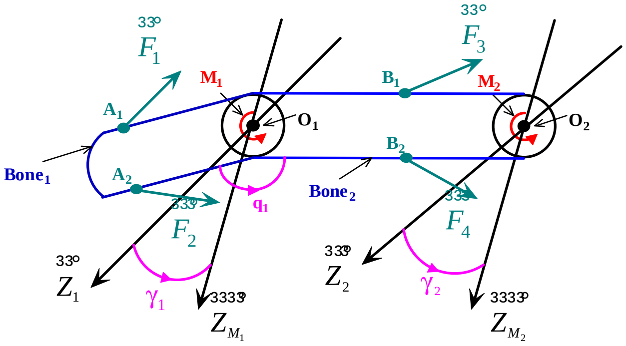

Figure 7 : Relation between Forces and Torques

In fig. 7, the axes Z_{M_1} and Z_{M_2} are the directional vectors for the torques created at O_1 and O_2 respectively. These vectors are defined in the coordinate system of the bone where the X axe is the axe of the bone. However the rotational axe of the bone (Z_1) does not necessarily belong to the (YZ) plan of the bone. Hence, (Z_1) can have an parameter angle γ_1 with Z_{M_1} .

The forward model is used essentially for the validation of the matrix $[T_{lt}]$:

Only one muscle (the i^{th} one) generates a force of magnitude K (Newton). This means that the vector of forces applied on the HHF system is $F = [0 \; \text{i} \; 0 \quad (K)_i \quad 0 \; \text{i} \; 0]$. Multiplying this vector by the matrix $[T_{lt}]$ will provide the resulting joints torques applied by this force on the HHF in our simulator. The same force is applied at the same position defined by the insertion points. The values of the torques obtained by the two methods are identical. Applying this method to all the muscles of the system will validate the numerical values of the $[T_{lt}]$ matrix, column by column.

B. Inverse Model

The inverse model consists of finding the muscles of the HHF that are responsible of a desired dynamical movement. The unknown variables are now the forces in the hand. The problem is to estimate what each muscle force must be to produce the required torques.

The problem formulated for forces analysis is an indeterminate one. Namely, the total number of unknown variables (45 muscles forces) exceeds the number of available equations of motion. Thus, muscle forces can be estimated by applying an optimization techniques [10].

However the choice of the optimization method is very important. Since the calculation must be made in real-time, the method chosen must converge quickly and steadily toward the optimum solution. The technique chosen is the “Penalized Augmented Lagrangian Multiplier method subject to equality and inequality constraints” [10]. This technique can be stated as follows:

$$\begin{cases} \text{minimize:} \\ L(x,\lambda) = f(x) + \sum_{i=1}^{m} \lambda_i \; h_i(x) + k \sum_{i=1}^{p} P_i\left[g_i(x)\right] \\ \text{according to the variables x and } \lambda \end{cases}$$

Where: $x \equiv F$ the muscles forces, *f(x)* is the objective function, λ is the Lagrangian multipliers, *m* is the number of equality equations, *p* is the number of inequality equations, *h(x)* is the equality constraints ($h(x) = [T_{lt}] \cdot [F] - [\tau]$), *g(x)* is the inequality constraints ($0 \le \mathrm{F} \le \mathrm{F}_{\max}$), *k* is a scalar that increases with each iteration, $k = 3^l$, *l* number of iteration, $P_i(x) = Max\left[0, g_i(x)\right]^2$ is the penalty term, if $g_i(x) > 0$ then $P_i(x) \neq 0$. This method converts a constrained optimization problem to an unconstrained one. It is chosen for its robustness and its fast convergence.

The objective function to minimize is the global effort of the forces [12]:

$$f = \sum_{i=1}^{45} \left(\frac{F_i}{(F_{\max})_i} \right)^2 \tag{7}$$

IV. Results

However the movements chosen in this paper are elementary ones. The purpose of these examples is to check the accuracy of the results. In elementary non-complex movements muscles that are activated can be anatomically predicted. Hence a qualitative evaluation of the results can be done. The movements produced are the closing and opening of the whole hand and the pinch movement. The entire duration of each movement is two seconds. The model is tested on multiple hand movements. The purpose of these examples is to check the accuracy of the results. In elementary non-complex movements muscles that are activated can be anatomically predicted. Hence a qualitative evaluation of the results can be done. The movement produced is the closing and opening of the whole hand. The entire duration of the movement is two seconds. The movements are divided into four phases: in the first period the entire HHF system is maintained stable for 0.3 sec. The second phase starts when the hand begins to close on itself following the sequence 1 - 2 - 3 in Fig. 8, this movement takes 0.7 sec to be accomplished. In the third phase, which has also a duration of 0.7 sec, the hand starts opening back, by following the order 4-5-6 (see fig. 8), to reach the fourth and final period where the hand is maintained in the same position (isometric) for 0.3 seconds. The time-step of the calculation is set at $\Delta t = 0.01$ sec. The forces values are observed and interpreted on the following graphical plots. The results shown in figures 10-12 belong to the index finger and the thumb of the first movement and figure 13 belong to the index of the second movement.

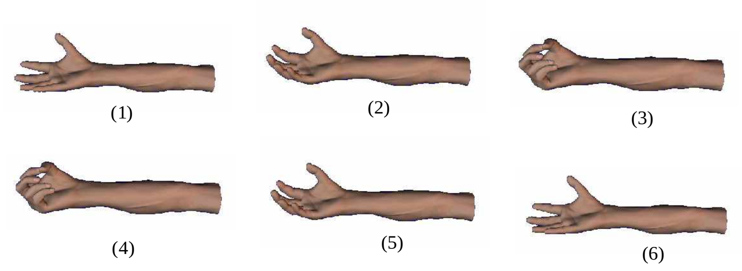

Figure 8: Opening-Closing hand movement

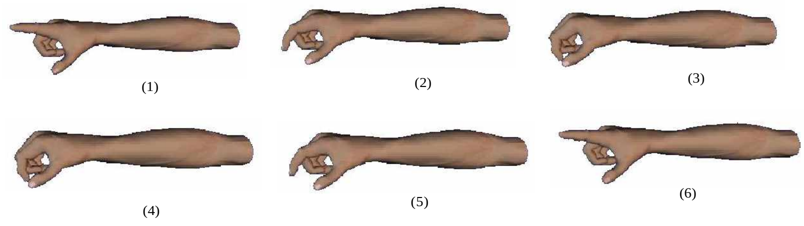

Figure 9 : Pinch Movement

The remarkable thing is that during the whole first movement the extensor indicis (EI) was inactive, while for the second movement the common extensor for the four fingers (EDC) is inactive. This phenomenon was expected. Kapandji [2] has verified that the EI is activated only when the index itself is producing a movement while the other fingers are motionless.

For the thumb, the forces are divided in two groups the intrinsic muscles and the extrinsic muscles. The forces in flexors and the thumb opposition muscles maintain balance against the gravity effect. However, the forces in the abductors of the thumb increase progressively with the movement. These muscles maintain the stability of the thumb during the movement.

For the other three fingers (the middle, the ring and the small) the solution is very similar to that of the index. Since all four fingers produce the same movement in this example. As for the wrist and the forearm, their muscle forces are constants, since they are motionless in this movement.

The forces in the index finger are greater than those of the thumb. This is due to the fact that in these movements the index generates a much bigger displacement than the thumb. The interosseous of the index produce the biggest force in this finger. Since the interosseous is the only muscle to flex the CMC joint. Plus, this muscle maintains the equilibrium of the CMC joint in adduction\abduction movement. Hence, a value of such importance was expected [11].

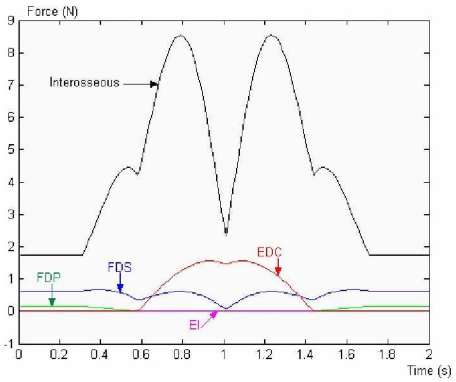

Figure 9 : Index finger muscle forces

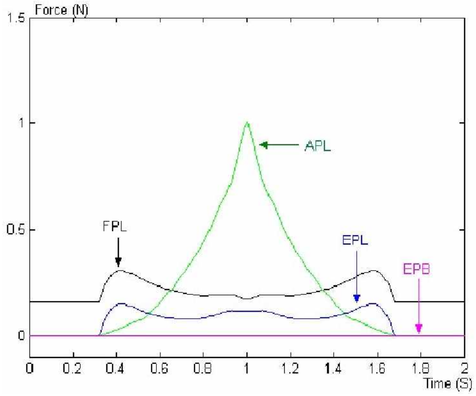

Figure 10 : Extrinsic muscles of the thumb

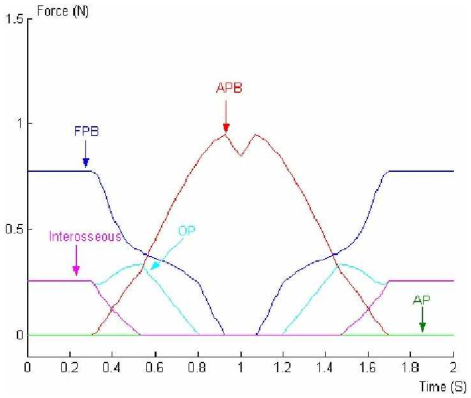

Figure 11 : Intrinsic muscles of the thumb

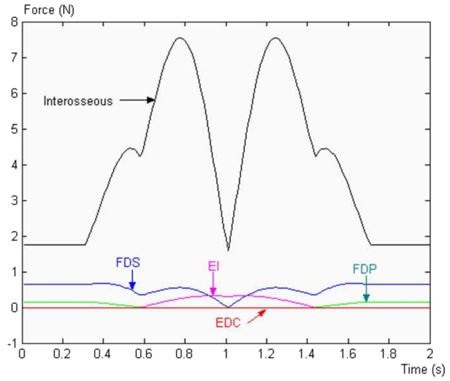

Figure 12 : forces in the index finger

V. Conclusion and further developments

The presented work concerned the muscle forces prediction in the HHF, to produce highly realistic simulation. An anatomical study of the HHF was studied. Some assumptions were chosen in order to simplify the complexity of the exact anatomy. A relation between the joints torques and the muscle forces was established. The forward and inverse problems were formulated. An optimization technique was adopted to predict the muscle forces in the HHF. The calculation of these forces was made according to the real-time requirements. The model was illustrated through a basic movement of the hand. Accurate results were found. However, a muscle force is not a measurable value. Hence, one of the limitations of the model is the lack of comparison with experimental data. The electromyography tests give only some qualitative results. To accomplish that, the cost function must take into account physical phenomena such as the work or the energy that the muscles produce. Such cost function will include measurable values to the model, like the activation of the muscles. This could help increasing the precision of results. Especially, when it comes to medical applications where every detail is necessary for any kind of surgery or hand replacement. Also, the experimental validation of the solution is necessary before beginning the design and realization of the robotic hands in the near future.

Reference

1. Eaton C. , A.N., CW. Oliver, *The mailbase hand surgery electronic mailing list.* J. hand surg 24 B, 1999. **145**: p. 145-147.
2. Kapandji, I.A., *articulation physiology.* Maloine, 1997. **volume 1, 5th Edition**.
3. chao E. Y. , K.N.A., *Determination of internal forces in human hand.* journal of the engineering mechanics division, 1978. **Vol. 104, No. EM1**.
4. Zatsiorsky M. V., R.w.G., Mark L. Latash, *Force and torque production in static multiphinger prehension: biomechanics and control. I. Biomechanics.* Biol. Cybern, 2002. **87**: p. 50-57.
5. Zajac, F.E., *Muscle and Tendon: Properties, Models, Scaling, and Application to Biomechanics and Motor Control.* Critical Reviews in Biomedical Engineering, 1989. **17**: p. 359-411.
6. Denavit J., R.S.H., *A Kinematic Notation for Lower-pair.* Mechanisms Based on Matrices, Journal of Applied Mechanics, ASME, 1955. **22**: p. 215-221.
7. Kamper Derek G. , T.g.H., William Z. Rymer, *extrinsic flexor muscles generate concurrent flexion of all three finger joints.* journal of biomechanics, 2002. **35**: p. 1581-1589.
8. Loeb, G.E., *The functional organization of muscles, motor units, and tasks.* Oxford University press, 1989: p. 23-35.
9. Chalfoun J., Renault M., Younes R., Ouezdou F.B., *Muscle Forces Prediction of the Human Hand and Forearm System in Highly Realistic Simulation.*, IROS 2004, Japan.
10. Maciel M.C. , G.N.S., *An augmented penalization algorithm for the equality constrained minimization problem.* Tendencias em Matematica aplicada e computational, 2002. **3, no. 2**: p. 171-180.
11. Long C. , M.E.B., G. Weiss, *Electromyographic kinesiology of the hand", part II. Third dorsal interosseous and extensor digitorium of the long finger.* Arch. Phys. Med. Rehab, 1961. **42**: p. 559-565.