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# Muscle Forces Prediction of the Human Hand and Forearm System In Highly Realistic Simulation

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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. 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 will be discussed and interpreted on an example simulating a basic movement 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. 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.

Many studies of the anatomy of the human hand were done during the last decade [1,2,3]. Using the information given by Charles Eaton [1], the properties of each muscle in the hand; its functionality and its effect on the joints were established. The insertion point of each muscle and the maximum force developed are given by A. Sereig [3].

The muscles are the motor part of the system, thus a relation between the forces generated in the tendons and the movement of the hand must be established. Many researches were done in this subject, for instance, the one presented by K.N.An [4] predicts the forces in the normal and abnormal hand during isometric hand function, mainly during the pinch position. Another, presented by Vladimir M. Zatsiorsky, studies the force and torque production in static multifinger prehension [5], and E.Y.Chao [6] 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 joints is taken into account. The computation of the forces is made, on line, during the movement of the hand.

At first, a brief description of the anatomy of the HHF parts is given. The system dynamic model, as well as the different parts that compose the dynamic equation will be presented. After that the forward model and the inverse model are formulated. These two models are defined as following: The forward model is used to validate the relation between the muscle forces and the joints toques. The inverse model is used to predict the forces in the hand during the movement. The inverse model is an indeterminate problem; namely, the total number of unknown variables exceeds the number of available equations. This is due to actuation redundancy. Therefore, an optimization technique is adopted in order to calculate theses forces. The results obtained are validated using an elementary movement of the hand. This movement is the opening and closing of the hand. Finally, further developments of the model are discussed.

## II. ANATOMY AND ASSUMPTIONS

### *A.* Anatomy

The osseous members of the human hand and the joints are represented in the fig. 1. [2]

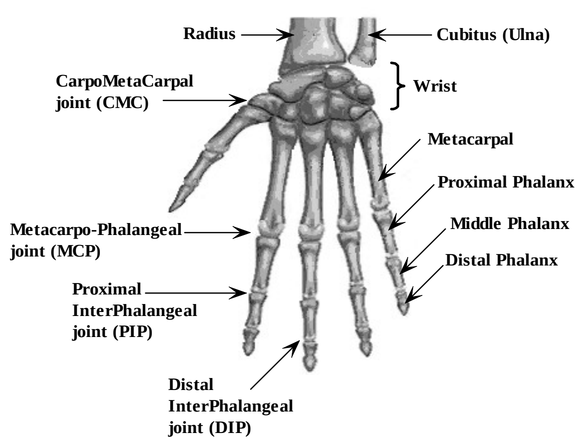


Figure 1. Osseous members and joints of the HHF

Muscle apparatus of the hand can be subdivided in two groups: extrinsic and intrinsic muscles. The muscles of the first group are long and powerful. They begin on the bones of the forearm and are attached to the bones of the hand. The intrinsic muscles are situated on the hand. While the contractile parts of the extrinsic muscles are situated on the forearm. In the extrinsic apparatus one can distinguish the carpal muscles, the four fingers muscles and thumb muscles. The radio-carpal joint (wrist joint) has two own flexors (flexor carpi radialis, FCR and the flexor carpi ulnaris, FCU) and two own extensors (extensor carpi radialis, ECR and extensor carpi ulnaris, ECU) from the side of radius and ulna correspondingly.

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. 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.

The interosseous and the lumbricals are intrinsic muscles of the hand. The interosseous are attached to the metacarpal bones and the proximal phalanx. There are three interosseous palmaris, one for the index (IP1), the ring (IP2) and the small (IP3). They contribute to abduction of these three fingers toward the middle finger. There are also four dorsal interosseous (ID1, ID2, ID3, and ID4) which have a more complex structure: each tendon has two portions, which are attached to neighboring metacarpal bones. They are responsible of the adduction and abduction movements of the MCP joints of the fingers. The particularity of lumbricals is that they are attached not to the bones but to the tendons of EDC and FDP (see Fig.2).

Compared with other fingers the thumb is quite independent from the point of view of functioning of muscle apparatus. Its extrinsic apparatus consists in four muscles: long flexor of the thumb (flexor pollicis longus, FPL), long and short extensors (extensor pollicis longus, EPL and the extensor pollicis brevis, EPB) and the abductor of the thumb (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.

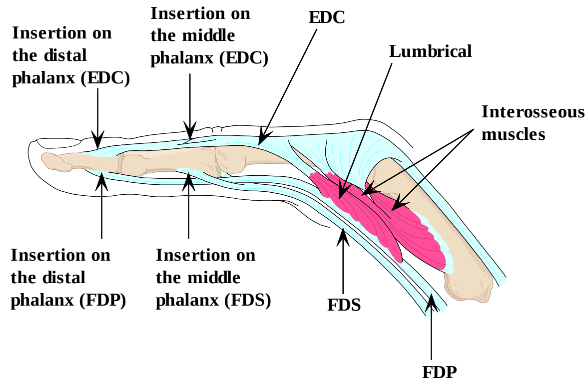


Figure 2. Extensor, flexors and interosseous

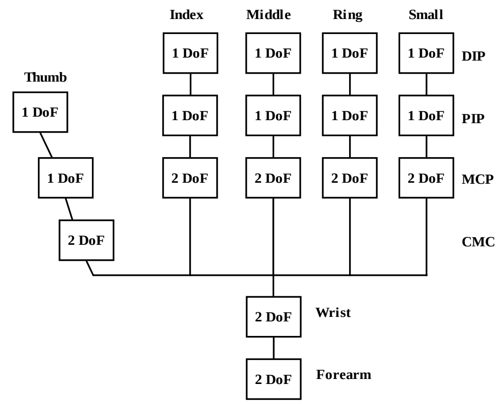


Figure 3. Degrees of freedom

## *B.* Assumptions

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

- The tendons are considered as inextensible wires.
- Due to the structure's complexity of the lumbricals muscles, (attachments on the other tendons and not on the bones), these muscles won't be modeled.
- It is important to notice that the joint's axes of the fingers are not parallel to each others (see Fig 4). They form different angles between adjacent axes and they differ from one subject to another. Thus, these angles are part of the parameters of the system. Also, the flexion/extension axe is not necessarily perpendicular or collinear to the abduction/adduction axe. Table 1 states the different angles for different individuals, and where I4 and T4 are the abduction/adduction axes of the index and thumb respectively.
- Each bone of the HHF has its own coordinate system, as shown in Fig. 5. 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 matrices. The

parameters of these matrices are defined according to the Denavit-Hartenberg description [7]. 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. The position of each bone is located by the angle that possess with the prior one, as shown in Fig. 6. The positive rotation is counterclockwise.

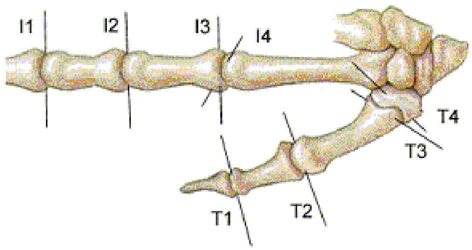


Figure 4. axes of the joints

TABLE I. AXES ANGLES MEASERED IN DEGREES

| | S1 | S2 | S3 | S4 |
|---|---|---|---|---|
| I3-I4 | 64 | 68 | 82 | 49 |
| I2-I3 | 14 | 8 | 6 | 24 |
| I1-I2 | 10 | 12 | 10 | 14 |
| T3-T4 | 49 | 40 | 68 | 57 |
| T2-T3 | 36 | 52 | 45 | 34 |
| T1-T2 | 23 | 13 | 17 | 8 |

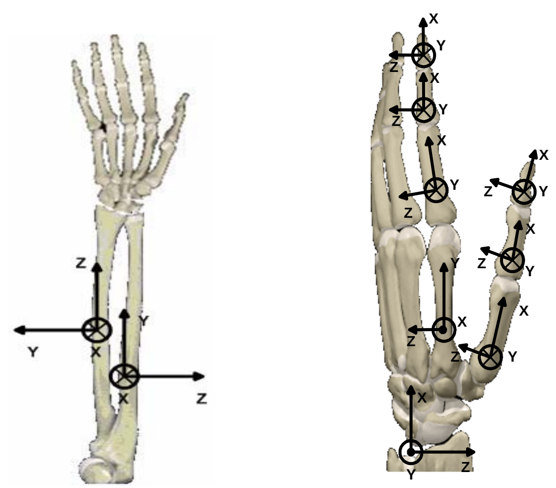

Figure 5. Axes of the HHF

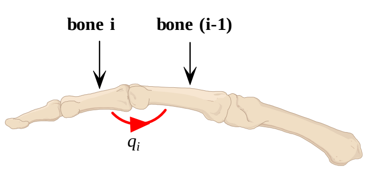


Figure 6. Orientation angle

- Any muscle which has an insertion on the phalanx will influence all the joints that its tendon passes by [8].
- 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 [8]. The movement inside these tissues is made without any friction. There are two pulleys for each finger (see Fig. 7), 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 who are inserted on the radius.
- Recent studies [9] 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, 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.

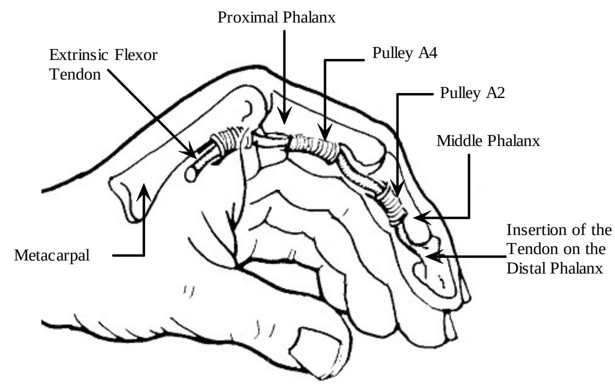


Figure 7. Pulleys of the index finger

## III. SYSTEM DYNAMIC MODEL

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

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

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 matrices 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 interaction 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) representing the relation between these two vectors.

The forward model by definition is when using equation (2) to compute the joints torques knowing the forces in the HHF. Wile the inverse model is when using (2) to compute the forces, in the HHF, responsible for a movement.

### *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 (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 articulated bones, (fig.8). 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 will give the following equation:

$$\begin{aligned}\mathrm{M}_1 &= O_1A_1\times\sin(\overrightarrow{A_1O_1},\overrightarrow{F_1})\times F_1\times\cos(\vec{Z},\overrightarrow{A_1O_1}\otimes\overrightarrow{F_1})\\ &+O_1A_2\times\sin(\overrightarrow{A_2O_1},\overrightarrow{F_2})\times F_2\times\cos(\vec{Z},\overrightarrow{A_2O_1}\otimes\overrightarrow{F_2})\end{aligned}$$

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:

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

Where for example:

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

$O_1A_1$ 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 [7]. Thus:

$$O_2A_1=TM_{2\text{-}1}\cdot O_1A_1 \qquad (3)$$
$$O_iA_j=[X_{O_iA_j}\quad Y_{O_iA_j}\quad Z_{O_iA_j}\quad 1]$$

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

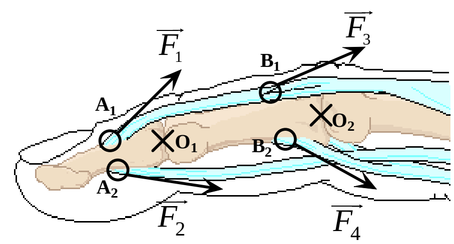


Figure 8. Forces application

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

The HHF system is modeled in the simulation software “ADAMS”. The model consists of rigid bodies (the bones) with the proper articulations design.

Only one muscle (the i[th] one) generates a force of magnitude *x* (N). This means that the vector of forces applied on the HHF system is $F=[0\cdots0\quad(x)_i\quad0\cdots0]$. Multiplying this vector by the matrix $[T_{lt}]$ will provide the resulting joints torques applied by this force on the HHF. The same force is applied at the same position defined by the insertion points in ADAMS. The values of the torques obtained by the two methods are identical. Applying this method on the entire system validates the numerical values of the $[T_{lt}]$ matrix.

### *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 formulated for forces analysis is an indeterminate one. Namely, the total number of unknown variables (45 muscles forces) exceeds the number of available equations (24 joints torques).

The most common method of resolving this kind of problem is the use of optimization technique [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 rapidly and steadily toward the optimum solution. Also the method must have a least number of parameters to manipulate. This will decrease the convergence time for each step. The technique chosen is the "Penalized Augmented Lagrangian Multiplier method subject to equality and inequality constraints" [11]. This technique can be stated as follows:

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

Where: $x \equiv F$ the muscles forces, *f(x)* is the objective function, *h(x)* is the equality constraints $h(x) = [T_{lt}] \cdot [F] - [\tau]$ and *g(x)* is the inequality constraints $0 \le F \le F_{max}$, $\lambda$ is the Lagrangian multipliers, *m* is the number of equality equations, *p* is the number of inequality equations, *k* is a scalar that increases with each iteration, $k = 3^l$, *l* number of iteration, $P_i(x) = Max[0, g_i(x)]^2$ 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.

Several cost functions can be chosen to find the solution. Namely, minimizing the energy produced by the muscles:

$$f = \sum_{i=1}^{n} F_i . \Delta l_i \qquad (5)$$

Where: $\Delta l_i$ is the muscle's length displacement.

However the muscle forces using this kind of cost functions are function of the displacement $\Delta l$. Thus, the muscle's model must be included in the equality and the inequality constraints. This will give an optimization problem subject to non-linear boundaries since the matrix $[T_{lt}]$ will also be a function of the displacement.

Thus, choosing this cost function will slow the prediction of the forces, and the calculation won't be made in real-time. Hence, in this paper the cost function chosen will include only the muscle forces.

The objective function to minimize is the global effort of the forces [9]:

$$f = \sum_{i=1}^{n} \left( \frac{F_i}{(F_{max})_i} \right)^2 \qquad (6)$$

Where n = 45 is the number of the muscles in the HHF.

## IV. RESULTS

The model is tested on multiple hand movement, like shaving and writing. However the movement chosen in this paper is elementary. The purpose of this example is to verify the accuracy of the results. The movement produced is the closing and opening of the whole hand. The entire duration of the movement is two seconds, and the movement is 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. 7, this movement takes 0.7 sec to be accomplished. The third phase, which has also a duration of 0.7 sec, is the inverse of the second one, it's when the hand starts opening back, by following the order 4-5-6 (see fig. 7), to reach the fourth and final period where the hand is maintained stable for 0.3 seconds.

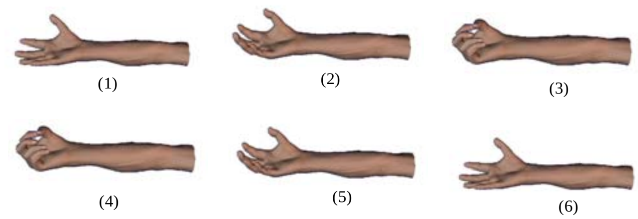


Figure 9. Sequence of the movement

The time-step of the calculation is set at $\Delta t = 0.01$ sec. This means that the joints torques, the muscle forces (optimization) and the graphical presentation of the hand must be computed in a maximum of 0.01sec. The forces values are transmitted to the MATLAB workspace, where the graphical visualization of the result is made.

The results shown in figures 10-12 belong to the index finger and the thumb muscles.

Since the hand is motionless during the first 0.3 sec, and the last 0.3 sec, the forces in the system are constants. In the index finger (fig. 10), only the flexor muscles (FDS, FDP and Interosseous) are contracted, in order to compensate the effect of the gravity. While the common extensor EDC and the index proper extensor (EI) are both inactive.

As the hand begins to close the flexor's forces start to decrease. However, the extensor's forces start to increase progressively. Also, the force in the Interosseous begins to decrease since the torque, at the CMC joint, created by the weight of the proximal phalanx is decreasing. The interosseous in the index finger is also responsible for the abduction/adduction movement. This is why the force produced by this muscle is much bigger than the other muscles of the index.

The remarkable thing is that during the whole movement the extensor indicis (EI) was 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.

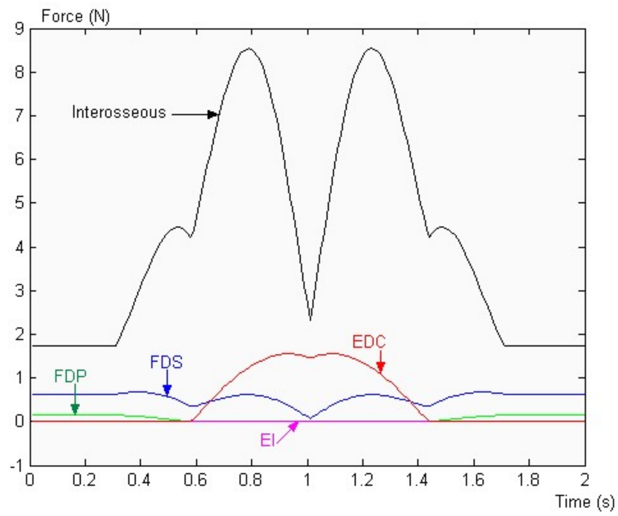


Figure 10. Index finger muscle forces

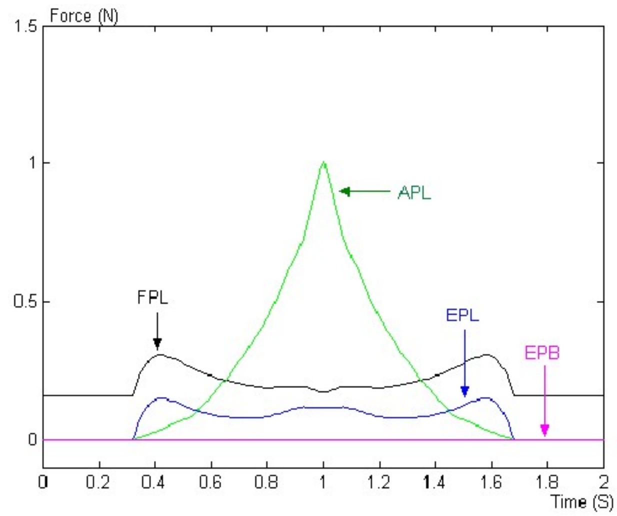


Figure 11. Extrinsic muscles of the thumb

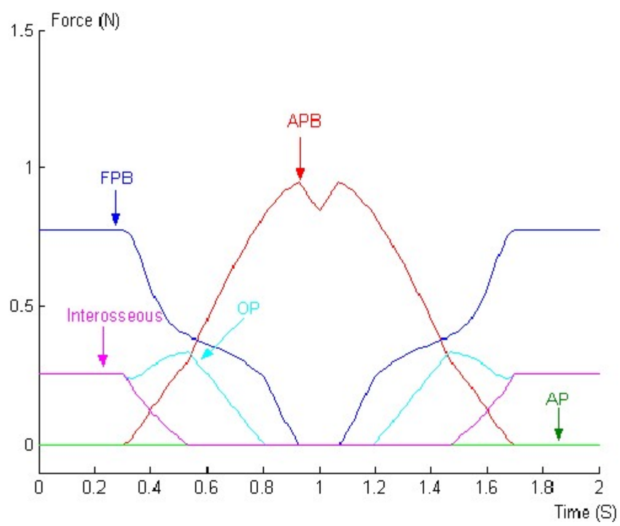


Figure 12. Entrinsic muscles of the thumb

## 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 thru 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 hand in the near future.

## References

[1] C. Eaton, AU. Ndukwe, CW. Oliver, “ The mailbase hand surgery electronic mailing list”, J. hand surg 24 B: 145-147, 1999.

[2] I.A. Kapandji “articulation physiology”, Maloine, Vol.1, fifth edition, 1997.

[3] A. Sereig, R. Arvikar, Biomechanical analysis of the musculoskeletal structure for medecine and sports, hemisphere publishing corporation, 1989

[4] K.N. An, E. Y. chao, “Determination of internal forces in human hand”, journal of the engineering mechanics division, Vol. 104, No. EM1, 1978.

[5] M. Vladimir Zatsiorsky, Robert w. Gregory, Mark L. Latash “Force and torque production in static multiphinger prehension: biomechanics and control. I. Biomechanics” Biol. Cybern. 87, 50-57, 2002

[6] E. Y. Chao, J.D. Opgrande, “Three-dimentional force analysis of finger joints inselected isometric hand functions”J. Biomechanics, Vol. 9, 387-396, 1976.

[7] J. Denavit and R. S. Hartenberg, “A Kinematic Notation for Lower-pair”. Mechanisms Based on Matrices, Journal of Applied Mechanics, ASME,Vol. 22, pp. 215-221, 1955.

[8] G. Kamper Derek, T. Georges Hornby, William Z. Rymer “extrinsic flexor muscles generate concurrent flexion of all three finger joints”, journal of biomechanics 35, 1581-1589, 2002.

[9] G.E. Loeb “The functional organization of muscles, motor units, and tasks” In: M.D. Binder & M.L. Mendell (Eds.) *the segmental motor system*. Oxford, Oxford University press, 23-35, 1989

[10] Han, S.P., "A Globally Convergent Method for Nonlinear Programming," Journal of Optimization Theory and Applications, Vol. 22, p. 297, 1977.

[11] M.C. Maciel, G.N. Sottosanto, “An augmented penalization algorithm for the equality constrained minimization problem”. Tendencias em Matematica aplicada e computational, 3, No. 2, 171-180, 2002.