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Distribution of handgrip force in the forearm muscles through static optimization

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Abstract. The purpose of this work was to distribute the hand grip force between the muscles of the hand by means of a non-linear model solved with static optimization. The force was measured in three pairs of flexion angles corresponding to the shoulder and elbow. (90°-90°, 135°-45°, and 160°- 30). A total of 22 participants completed the study, 6 men and 6 women between 18 and 25 years old. A MicroFET® handgrip dynamometer (0-200 pounds) and an adjustable angle arm support were used during the data collection. The moment arms of the forearm were predicted using a model proposed in the literature. The distribution of force was modeled as a non-linear problem of static optimization and solved with the fmincon optimizer of the Matlab® optimization toolbox. The results obtained in the calculation of the moment arm show that they decrease as the angle of flexion of the elbow decreases. The static optimization model used for the three scenarios related to the flexion angle of the elbow always assigned muscle force to the extensor muscles.
Keywords: Handgrip force, moment arm, distribution of force, static optimization.

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1 Introduction

The exertion of the grip force in a prolonged way is causal of musculoskeletal disorders associated with the upper extremities [1]. Because of this, the grip force provides objective information on the functionality of the upper extremity [2]. Then, the grip force is an indicator of the function of the hand [3]. According to The European Working Party on Sarcopenia in Older People (EWGSOP) [4], the grip force was the only recommended evaluation technique to measure muscle force and was the simplest method to evaluate muscle function in clinical practice. Hence, the hand grip force can be assessed with the static force produced by tightening a dynamometer [5]. Moreover, the literature supported the idea that the measurement of the grip force performed with a dynamometer can have value as predictors of important results [6]. Therefore, the measurement of the maximum grip force is a relevant component to follow the individual in the different stages of their daily life and its measurement is performed with a dynamometer with which the primary force is estimated by the flexor muscles of the hand and forearm [7].

The majority of the grip force is produced by the forearm muscles, which can be classified by their position as anterior (flexors) and posterior (extensor) [8]. Then, these muscles are the extensor digitorum communis to the index, middle, ring, and small fingers, extensor digiti quinti, extensor indicis proprius, extensor pollicis longus, flexor digitorum superficialis, flexor digitorum profundus, flexor pollicis longus, pronator quadratus, palmaris longus, pronator teres, and brachioradialis [9]. However, The flexor muscles are the primary ones in the grip, but more discomfort of the forearm extensors was reported [10]. Therefore, musculoskeletal disorders of the forearm are considered a public health problem [11].

There is limited knowledge about the muscle force of the grip, which includes the flexor muscles and the activation of the extensor muscles [12]. Additional to the previous situation, the variable that the geometry of the forearm muscles can be altered by the posture of the wrist and the elbow can be added [13]. Consequently, the analysis of the forces in the human musculoskeletal system lies a problem with unknown variables of the system that exceeds the equilibrium equations and the relation of constraints [14].

Therefore, the mathematical optimization has been used as a noninvasive tool to determine muscle force in the coordinated movement of multiple joints, and historically this problem has been known as redundant in biomechanics [15]. The classic notion of redundancy is that the body has more muscles than degrees of freedom (DoFs), and many muscles act on the same number or fewer joints, arguing that the central nervous system (CNS) must solve an optimization problem to select and implement specific muscle activation patterns to a theoretical set of infinite possibilities [16]. To resolve the redundancy problem in finding muscle activation levels, it is typical to use optimization methods such as static optimization and dynamic optimization with different types of cost functions [17].

Hence, the method of static optimization has proven satisfactory results in its desired purpose [18]. Therefore, it can optimize criteria like muscle force, muscle stress, muscle activation, and the ratio between the force applied by the muscle and the maximum isometric force [19]. Then, the objective functions are subject to equalization restrictions to guarantee equilibrium such as moments and inequality restrictions therefore that the calculated force is equal to zero or greater but without exceeding its maximum value [20].

In consequence, there have been multiple studies of the distribution of muscle force in the forearm through static optimization. However, the way to perform the force with the hand has been specific for every study. For example, the muscular force during the forearm flexion during the lifting of a load was distributed using static optimization [20]. Meanwhile, a cylinder grasping movements were captured and using the inverse dynamics and static optimization the muscle force was distributed in the forearm muscles [11]. Furthermore, during the pushing phase in the propulsion of a wheelchair, a model considering the trunk, the arm, and the forearm sections was constructed, and the results of the distribution of muscular forces between static and dynamic optimization were compared [21]. Then, the way to perform the force with the hand (or task) and the flexion of the upper limbs make the results of the distribution of forces different.

Considering the background described, the purpose of this study was to determine and distribute the force of the flexor and extensor muscles of the forearm when performing grip force and varying the angle of the elbow in tasks above the shoulders. The article describes in section 2 the materials, the sample, the procedure to determine the grip force, the calculation of moment arms, and how the problem was modeled mathematically. Next, we present the results obtained from the moment arms model, muscular activation, and the distribution of muscular force. Then, the programming code used in Matlab® is presented. Afterward, the results are discussed in opposition to the findings of other researchers. Finally, it concludes commenting the results and future work is recommended

2 Methodology

In this section, the methodology to determine the muscles force of the forearm when handgrip force is performed at different angles of elbow flexion is presented. The study design was cross-sectional, quasi-experimental, and exploratory. Figure 1 shows the schematic structure of the proposed estimator.

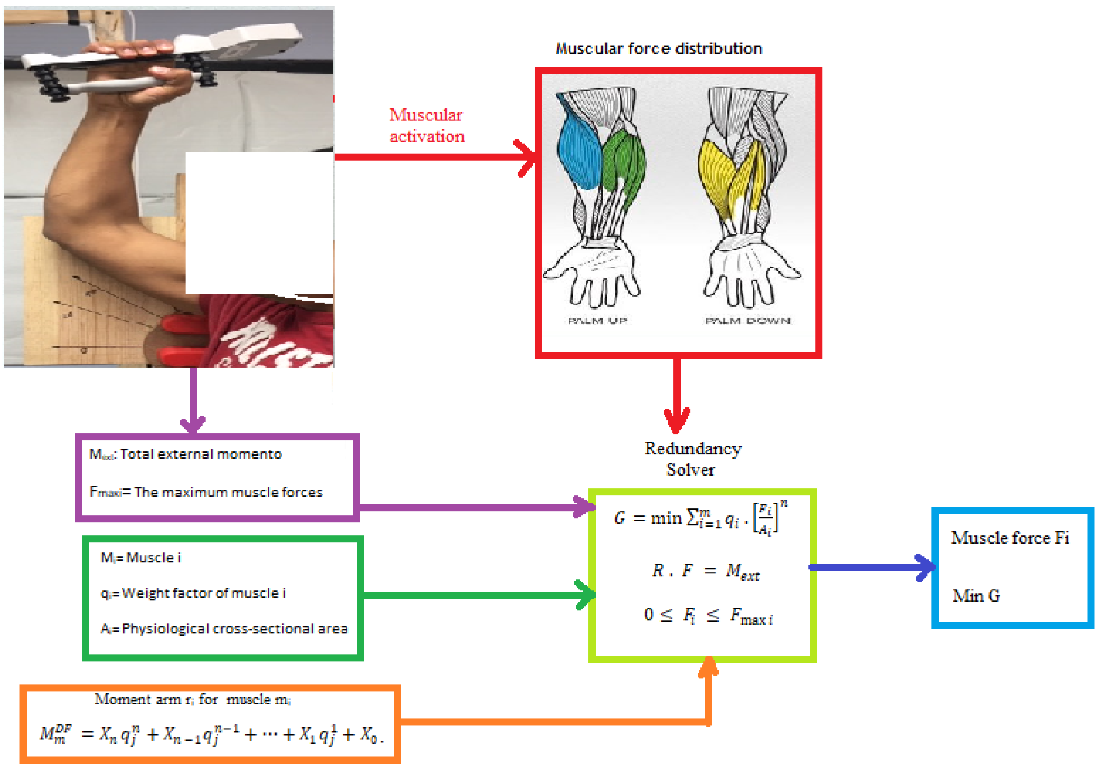

Figure 1 Schematic structure of the proposed estimator.

2.1 Sample

The study to determine the grip force was conducted with 22 volunteers (16 men and 6 women between 18 and 25 years), without musculoskeletal problems.

2.2 Materials

Two devices were used during the data collection. A MicroFET® handgrip dynamometer [22], and an Angled Adjustable Arm Support (see Figure 2).

Figure 2. Dynamometer and Arm support.

2.3 Procedures

Here, we present the design of the experiment to distribute the grip force between the AN, BR, FCR, ECRL AND ECU muscles of the forearm.

2.3.1 Input data captured in the laboratory

The procedure was reviewed and approved by the Ethics and Bio-Ethics Committee of the Autonomous University of Ciudad Juarez, México. The participants were informed about the approval and the purpose of the procedure, and they signed the consent form. In order to standardize the force measurement, the Caldwell protocol [23] was applied during the data collection.

The measurement procedure is explained below. First, the guide for support was placed at the elbow high of each participant. Second, the participant was placed next to the guide structure, and the procedure was explained emphasizing in showing three pairs of flexion angles corresponding to the shoulder and elbow (90°- 90°, 135°- 45° and 160°- 30). Third, an initial test was conducted to give clarity about how to execute the exercise considering the variations of angles. Fourth, the MicroFET® dynamometer was delivered to the participant with 1-7/8 -inch opening in the grip. Fifth, grip force with and without arm support was recorded. To minimize the fatigue effects, a rest period of 40 minutes between each muscular contraction was allowed for every participant.

A 3x3 Latin Squares was used to determine the order of execution for each participant. The procedure was carried out in the facilities of the Ergonomic Product Design Laboratory at the Autonomous University of Ciudad Juarez, México.

2.3.2 Input data captured by mathematical processing

2.3.2.1 Moment in the forearm

The hand and the forearm were considered as a single element. The moment was calculated on the palm of the hand when the grip force was performed. It was assumed that the hand forms a cylinder with a diameter equal to the opening of the lever of the dynamometer at the time of making the grip. In this case, we take 50% of the opening of dynamometer (1 7/8 inches) as the radius of rotation of the grip force.

2.3.2.2 Moment arms

The moment arms were evaluated for the forearm muscles. The related muscles were: anconeus (AN), brachioradialis (BR), the flexor carpi radialis (FCR), extensor carpi radialis longus (ECRL), and extensor carpi ulnaris (ECU). The moment arms of muscle *m* in millimeters are determined with the model proposed by [24]. The model uses equation (1).

$$M_m^{DF} = X_n q_j^n + X_{n-1} q_j^{n-1} + \cdots + X_1 q_j^1 + X_0. \quad (1)$$

Where:
DF= Degrees of freedom used to determine the moment arm of a muscle m.
X_i = Stands for coefficients a_i, b_i, c_i, or, d_0, for wrist radial/ulnar deviation (WRU), wrist flexion/extension (wFE), elbow flexion/extension (eFE), or shoulder flexion/extension (sFE). i varies from 0 to n; n is the order of polynomial fitting the data.
q_j= is the joint angle, in degrees (q_1, q_2, q_3 for wrist radial/ulnar deviation (WRU), or wrist flexion/extension (wFE), elbow flexion/extension (eFE) and shoulder flexion/extension (sFE) respectively).

2.3.3 Distribution of force in the muscles

For the distribution of the total force in the forearm muscles, we use the static optimization model used by [20] in its research. The objective function is shown in equation (2). Next, the equilibrium restriction for the total torque is represented by equation (3). Finally, equation (4) presents the limits in which the variable of interest can be moved.

$$G = \min \sum_{i=1}^{m} q_i \cdot \left[\frac{F_i}{A_i}\right]^n \quad (2)$$

$$R \,.\, F = M_{ext} \quad (3)$$

$$0 \leq F_i \leq F_{\max i} \quad (4)$$

where:
G = is the objective function.
m = is the number of design variables
q_i = represent the weight factors of design variables.
F_i =are the forces for the assumed muscles.
n = is the power of the objective function, where n= 2, 3.
Using Ai =1 equivalent to use muscle forces as design variables whereas, using Ai= physiological cross-sectional area (PCSA) for muscles equivalent to use muscle stresses as design variables. Pennation angles of muscles are not taking into account.
R= matrix of the moment arms of muscles
F= matrix of muscle forces
M_{ext}= total external moment.
$F_{max\ i}$= The maximum muscle forces.

We propose as an objective function to minimize the muscle activation given by equation (5)

$$q_i \cdot \left[\frac{F_i}{A_i}\right]^2. \quad (5)$$

The input values for the model are shown below. The moment arms, gotten with equation (1), are shown in Table 1. The Physiological Cross-Sectional Area (PCSA) was taken of K. R. S. Holzbaur, W. M. Murray, G. E. Gold, and S. L. Delp [25]. Table 2 shows the PCSA of muscles used in this research. The maximum force was calculated based on what was established by AGREGA EL NOMBRE [26]. Table 3 shows the muscular F_{max}. Finally, the weight factors used for each muscle were the inverse of moment arms.

Table 1. Moment arms of forearm muscles.

Moment Arms (mm)				
90°				
AN	BR	FCR	ECRL	ECU
-9.65433194	68.673641	2.83473	29.945529	-8.52229
45°				
AN	BR	FCR	ECRL	ECU
-7,830148248	41,47784263	2,6193825	16,62154988	-7,6793725
30°				
AN	BR	FCR	ECRL	ECU
-7,69946558	31,810283	2,22117	11,682447	-6,36421

Table 2. Physiological cross-sectional area (PCSA).

		PCSA (cm^2)		
AN	BR	FCR	ECRL	ECU
1.3	14.4	3.9	2.7	2.3

Table 3. Muscular F_{max}.

			F_{max}		
Elbow angle	AN	BR	FCR	ECRL	ECU
90°	713	100	2428	229	807
45°	882	166	2638	415	900
30°	873	211	3026	575	1056

3 Results

Table 4 shows the mean value of grip forces and moments captured in the laboratory test with the 22 participants for the angles 90°, 45° and 30° of elbow flexion above the head. Next, the calculated moment in the hand is exposed based on the mean value of grip forces and the opening of the dynamometer.

Table 4. Handgrip force and moment.

Elbow angle (degrees)	90°	45°	30°
Mean Handgrip force (Newton)	289,08	290,29	282,32
Moment (Newton-mt)	6.88	6.91	6.72

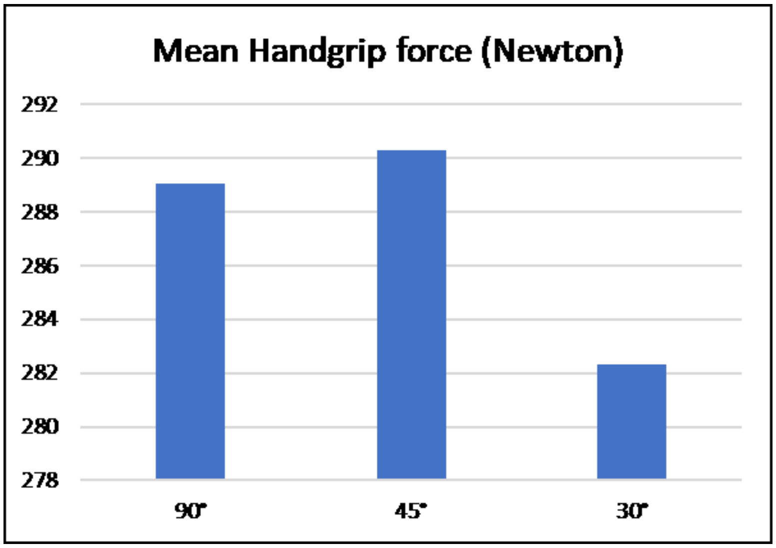

Figure 3. Mean handgrip force for different elbow flexion angles (Newton). and Figure **3** describe the behavior of the grip force measured with a dynamometer and the moment generated in the palm of the hand.

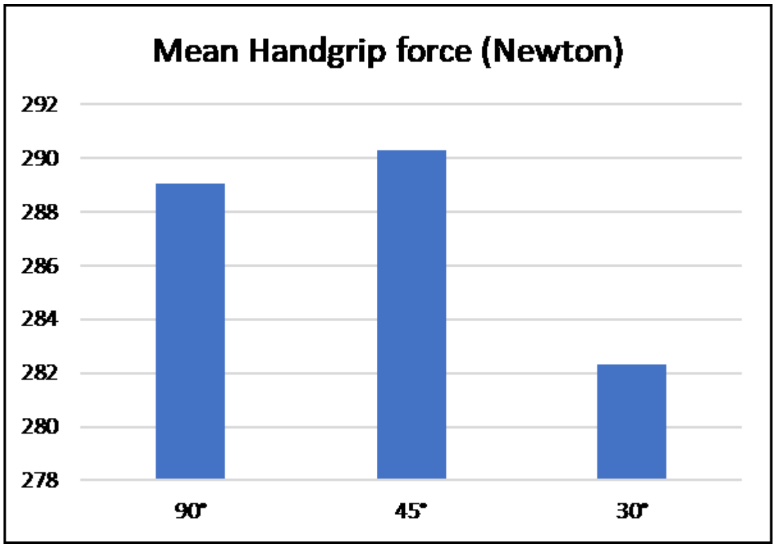

Figure 3. Mean handgrip force for different elbow flexion angles (Newton).

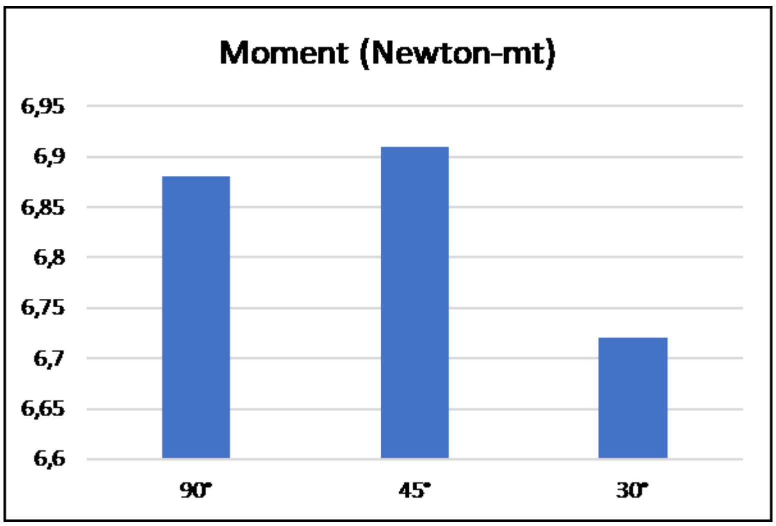

Figure 3. Moment for different elbow flexion angles (Newton-mt).

The muscle force was calculated for the AN, BR, FCR, ECRL, and ECU muscles, and it was distributed based on a single objective function. For this purpose, the variation of moment arms, total moment, and maximum forces were made based on the angle of flexion of the elbow. Table 5 shows the optimized values of the objective function and the values of the distributed muscular force for each muscle.

Table 5. Values of the objective function and the values of the distributed muscular force for each muscle.

Elbow angle	$q_i \cdot \left[\frac{F_i}{A_i}\right]^2$	AN	BR	FCR	ECRL	ECU
90°	6.76×10^{10}	0.01	99.94	7.12×10^{-15}	0.65	0.03
45°	3.20×10^{11}	0.04	166.24	8.22×10^{-17}	0.93	0.14
30°	6.66×10^{11}	0.10	210.90	1.60×10^{-13}	0.99	0.21

In **¡Error! No se encuentra el origen de la referencia.**, we observe as the muscle activation increases while the angle of the e lbow decreases. Then, in **¡Error! No se encuentra el origen de la referencia.**, it is observed how the force of the extensor muscles is distributed and increased as the angle of flexion of the elbow decreases. However, the only flexor muscle is assigned a nonsignificant force value. On the other hand, Figure 4 shows how the extensor BR is the one that distributes the highest force value, which increases as the angle of the elbow decreases.

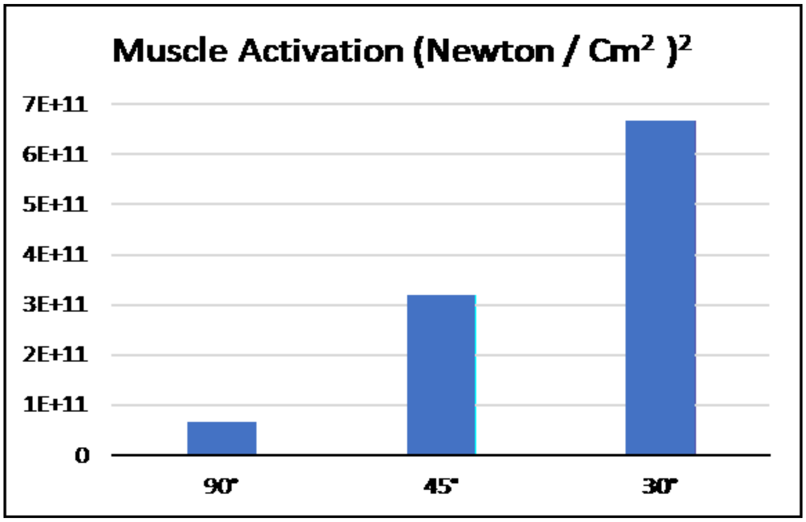

Figure 5. Muscle activation for different elbow flexion angles.

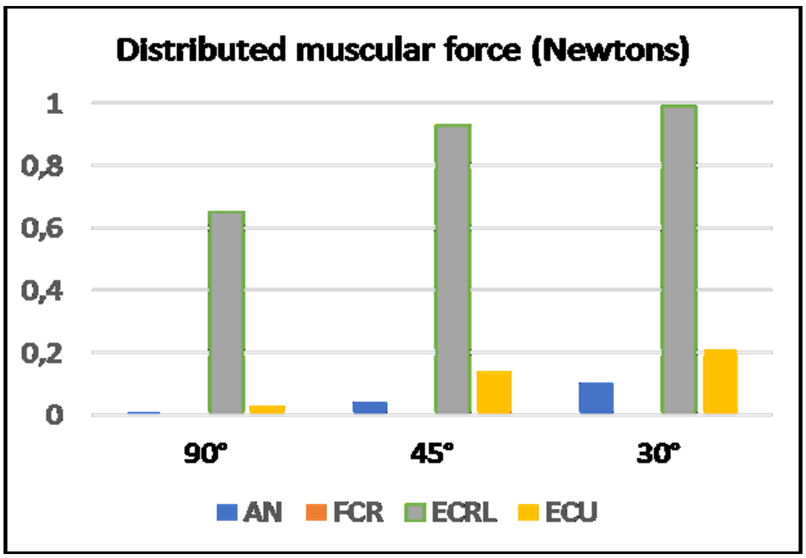

Figure 6. Distributed muscular force for different elbow flexion angles

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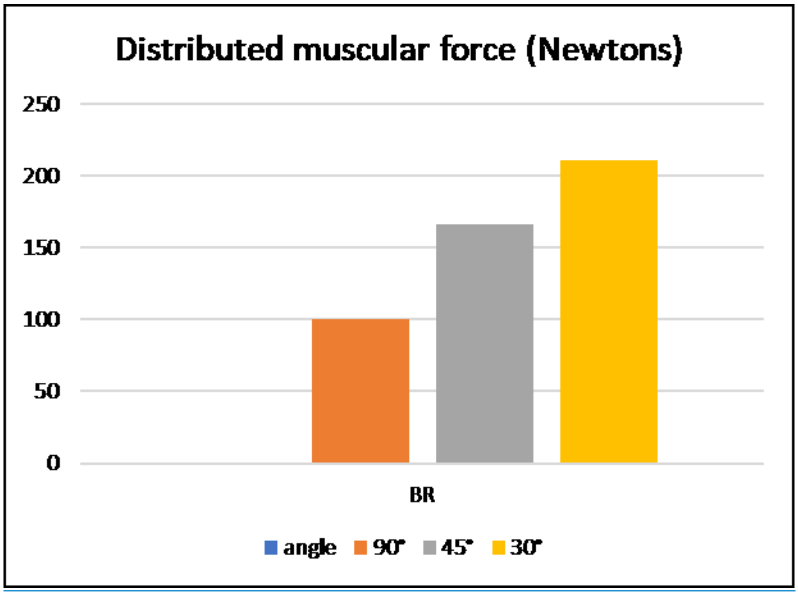

Figure 4. Distributed muscular force for different elbow flexion angles.

4 Program Code

The 2019 Matlab® software of The MathWorks-Inc was used to model the redundancy problem as a non-linear optimization problem. The code used with the Matlab® fmincon algorithm is shown below in Figure 5.

```
function [cost] =funobj(f)
cost
(103*(f(1)/0.00013)^2+14*(f(2)/0.00144)^2+352*(f(3)/0.00039)^2+33*(f(4)/0.00027)^2+117*(f(5)/0.00023)^
end

lb=[0,0,0,0,0];
ub=[713.01,100.23,2428.35,229.87,807.73];
A=[];
b=[];
%f=[];
Ae=[0.009654332 0.068673641 -0.00283473 0.029945529 0.00852229];
be=(6.8837175);
f0=[2428,2428,2428,2428,2428];
[f, cost]=fmincon(@funobj,f0,A,b,Ae,be,lb,ub);
```

Figure 5. *Program code.*

5 Discussion

When calculating the moment arms with the equation (1) proposed in the model of Pigeon, Yahia, and Feldman [24], it was determined that the moment arms changed with the variation of the angle of flexion of the elbow. Then, it was observed that moment arm decrease as the angle of flexion of the elbow decreases. Consequently, an increase in muscle force could be expected to compensate for the loss of the moment arm and thus compensate for the total moment in the musculoskeletal segment.

When optimizing, always the extensor muscles were assigned with force values. Meanwhile, the only flexor muscle was not assigned a force value. This coincides with the hypothesis of J. P. M. Mogk and P. J. Keir [10] which reported that more discomfort of the forearm extensors was reported. However, it would be expected that the flexor muscle had a high value of the assigned force since it is the one that works when grip force is performed. A possible answer to this difficulty is what was raised by J. H.

Challis and D. G. Kerwin [26], who postulated that the response of muscle force depends on factors such as muscle length, velocity, and degree of muscle fiber activation, and these optimization models do not contemplate such elements.

Finally, it was observed that the value of the distributed forces increased as the angle of the elbow decreased. Then, the muscular force of the AN ranged from 0.01 N to 0.10 N, the BR ranged from 99.94 N to 210.9 N, the ECRL ranged from 0.65 N to 0.99, and the ECU ranged from 0.03 N to 0.21 N.

6 Conclusions

In this document, the design of an experiment to distribute the grip force between the AN, BR, FCR, ECRL, and ECU muscles of the forearm was presented. The experiment started with the capture of the grip force using a dynamometer above the head at different angles of flexion of the elbow, followed by the FOLLOWED BY THE determination of the total moment in the forearm, the calculation of the moment arms by means of a model presented in the literature, and ends with the distribution of forces in the muscles of the forearm by means of static optimization.

The results obtained in the calculation of the moment arms showed that they decrease as the angle of elbow flexion decreases. On the other hand, the static optimization model used for the three scenarios related to the flexion angle of the elbow always assigned muscle force to the extensor muscles. However, the model never assigned significant value to the flexor muscle included in the model. But it was observed that the muscular forces assigned to the extensor muscles increased as the angle of the elbow decreased.

Future work can be related to the development of robust mathematical models including more muscles and intrinsic variables to the muscles.

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