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# Evaluation of Grip Force Using Electromyograms in Isometric Isotonic Conditions

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# Evaluation of Grip Force Using Electromyograms in Isometric Isotonic Conditions

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The purpose of this study was to develop a relationship to evaluate the grip force ($force_{rel}$) using the electromyogram ($EMG_{rel}$) of the flexor digitorum superficialis (FDS) and of the extensor digitorum (ED) according to the flexion-extension wrist angle ($\theta_{f-e}$) and to the pronation-supination forearm angle ($\theta_{p-s}$).

Fifteen participants had to exert 3 levels of grip forces in 4 positions of the wrist combined with 3 positions of the forearm.

The relationship is:

$$force_{rel} = 0.0045 \cdot \theta_{f-e} \cdot EMG_{rel}(FDS) + 0.48 \cdot EMG_{rel}(FDS) - 0.0014 \cdot \theta_{f-e} \cdot EMG_{rel}(ED) - 0.0016 \cdot \theta_{p-s} \cdot EMG_{rel}(ED) + 0.4 \cdot EMG_{rel}(ED)$$

This relationship can be used to estimate grip force for levels of strength lower than 50% of the maximal voluntary contraction.

cumulative trauma disorders biomechanical stresses upper limb

## 1. INTRODUCTION

Since the beginning of the 1980s, the number of cumulative trauma disorders (CTD) for which compensation has been granted has been steadily increasing (Ayoub & Wittels, 1989; Caisse Nationale de l'Assurance Maladie des Travailleurs Salariés [CNAMTS], 1994). CTD affect the joints (bursitis, synovitis), tendons (tendinitis, tenosynovitis), and nerves (compression syndromes). Among the CTD having a professionally-

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related contribution, the carpal tunnel syndrome (CTS) is one of the most predominant due to its prevalence in certain sectors of activity (Silverstein, Fine, & Armstrong, 1987). CTS causes sensory-motor disorders in the zone innervated by the median nerve, as a result of the compression of this nerve in the carpal tunnel.

CTD results from an imbalance between biomechanical stresses of either a professional (high forces, high degrees of repetitiveness, extreme angles of articulation, vibration and shock during job duties) or an extra-professional nature (sports, do-it-yourself, etc.), but it depends also on individual functional capacities related to a large number of factors (physical constitution, age, gender, life-style habits, etc.). There are numerous consequences of this type of pathology for both the individual (occupational disability, medical treatment) and for employers (loss of productivity and sick leave; Ayoub & Wittels, 1989).

One approach that can be taken to solve the problem of occupational CTD consists of evaluating the imbalance between the biomechanical stresses and functional capacities in order to be able to find ergonomic solutions. This approach assumes that the biomechanical stresses and functional capacities are measured in terms of positions of articulation, repetitiveness of different movements, and force. Articular positions can be directly measured, using either goniometers, torsiometers, or both, attached to the upper limbs of the worker, or an optical system for the analysis of movement. It is possible to characterize and quantify the repetitiveness of movements using the measurements of articular position, notably by calculating the first, second, or both, derivatives of the signal given by the angular sensors. On the other hand, the force is not always directly measurable without hindering the working movement. It is, therefore, necessary to use an indirect method of force measurement, such as integrated surface electromyogram (EMG; Armstrong, Chaffin, & Foulke, 1979; Silverstein, Fine, & Armstrong, 1986) which is proportional to the force developed by a muscle in static conditions. Henceforth, it would appear to be sufficient to record and process the EMG in order to evaluate force levels if certain precautions are taken.

In the case of CTS, the type of effort that is frequently cited as a major cause is that of grasping as it is often used in the holding of tools and in instances where high levels of force must be exerted. Nevertheless, the evaluation of the grip force by means of EMG poses certain problems. The EMG depends on the position of the electrodes with respect to the muscles, which can vary as a function of the angle of pronation, supination, or both, of the forearm and the muscle, and on the conducting volume, which varies as a function of muscle length and in this particular case with the angle of flexion-extension of the wrist. Furthermore, because the force is also a function of muscle length, it is also a function of these same two angles. Thus, the force and the EMG both depend on the flexion-extension angle of the wrist and on the angle of pronation-supination of the forearm. In order to account for these different factors, different levels of effort for different hand positions can be evaluated in the laboratory, and a linear regression can be performed on the results to establish an empirical relationship between them.

A grip effort involves not only the flexor muscles of the fingers, but also the extensor muscles. The role of this co-contraction of agonistic and antagonistic muscles is most likely to stabilize the wrist. It is, therefore, necessary to take this simultaneous activity of antagonistic muscles (finger extensors) into account in order to evaluate grip efforts.

So, the objective of this study was to develop an empirical relationship that can be used to evaluate grip force in both isotonic and isometric conditions, using a relationship linking the EMG of the flexor digitorum superficialis, the extensor digitorum, the flexion-extension angles of the wrist, and the angles of pronationsupination of the forearm. The formulation of this model must remain relatively simple so that it can be used in the field. Similarly, the collection and treatment of the EMGs should also be clear and standardized.



## 2. MATERIALS AND METHODS

This study was carried out on 15 right-handed female participants. The participants were medically examined and informed of the procedure and objectives of the experiments beforehand, and the experiments were authorized by the Consultative Committee for the Protection of Individuals participating in Biomedical Research Studies. All participants were healthy students without musculoskeletal past and did not exercise regularly. The mean age (*SD*) of the participants was 23.5 (2.7) years, the mean height 1.65 (0.06) m, and the mean weight 57 (5.8) kg.

The participant was placed in a seat that could be adjusted (height, depth of the seat, and tilt of the seat back) to her anthromorphological characteristics. The trunk of each participant was strapped to the seat back in order to prevent any changes in the seated posture during the measurement of the grip force. The elbow was bent at 90°, the right forearm was placed in a supporting armrest. A goniometer (Penny & Giles®) was attached with a double sided adhesive tape to the participant's right wrist in order to measure the angles of flexion-extension. In the same manner, the angles of pronation-supination were recorded with a torsiometer (Penny & Giles®) placed on the right forearm. The positions of the goniometer and of the torsiometer were defined according to the recommendations of the manufacturer. The handle was developed in our laboratory; it was equipped with a force sensor to measure the grip force, and with two precision potentiometers (MCB®) to measure the position of the handle in the flexion-extension plane of the wrist and in the pronation-supination plane of the forearm. The span of the handle could be adjusted to suit the anthropometric characteristics of the participant's hand, but all participants used the handle with the standard span which was 4.5 cm (Mathiowetz, Weber, Volland, & Kashman, 1984). The position of the hand was, thus, imposed by the orientation of the handle and fixed with a screw (see Figure 1).

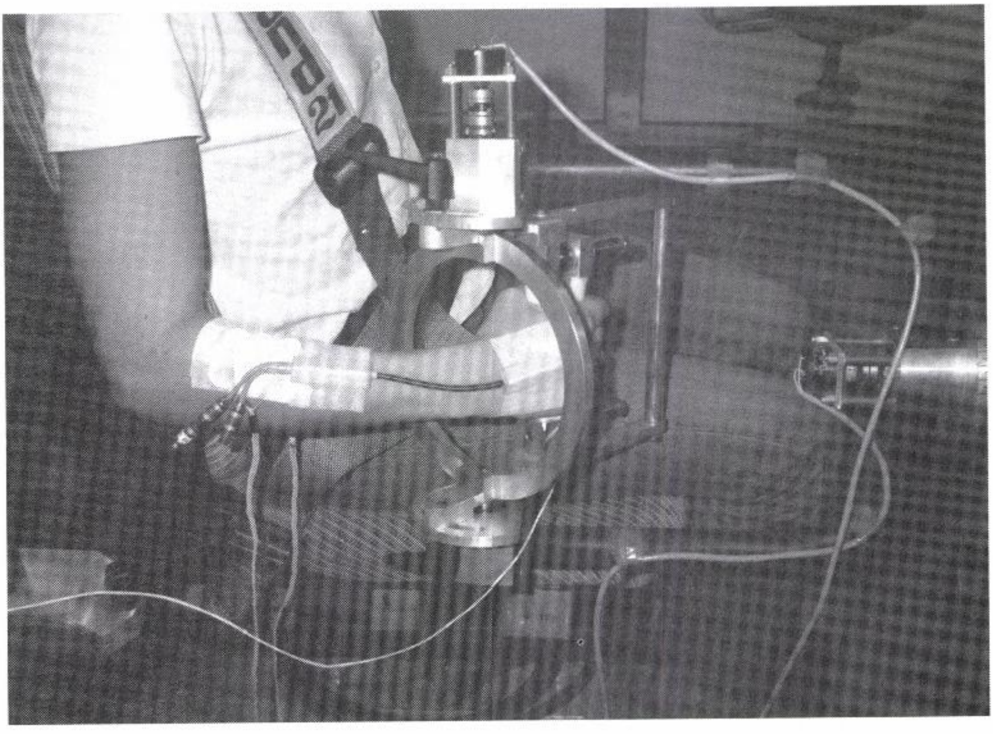

**Figure 1. The experimental device.**

The positions of the wrist were maximal flexion, neutral position (the carpal bones are aligned in approximately the same direction as the forearm), a position in medium extension chosen by the participant where she felt that the grip force was at a maximum (approximately 30° in extension [Ranaivosoa, 1992]), and maximal extension. For every wrist position the forearm is either in pronation, neutral, or in supination. Twelve hand positions (4 in flexion-extension of the wrist and 3 positions of pronation-supination of the forearm) were imposed on each participant.

Each participant exerted 3 efforts for each position of the wrist and forearm: maximal voluntary contraction (MVC), 20% of the MVC, and 50% of the MVC. An electronic device was used to visualize a signal delivered by the force sensor inserted in the handle, as well as the desired force levels. The participant was, thus, required to superpose the signal coming from the handle and the signal corresponding to either 20 or 50% of the MVC. The maximal voluntary contraction efforts were systematically repeated twice, with the efforts being separated by a rest time of 3 min in order to eliminate the possibility of muscular fatigue (Scherrer & Monod, 1960). Only the higher of the two MVCs was considered in the experiments. The MVC was maintained for 2 s, and the sub-maximal efforts (20% and 50% of the MVC) were maintained for 10 s. Only the first 2 s of stable force maintenance were used in the calculation of the force and the evaluation of the corresponding integrated EMG. Because of the visuomotor feedback needed to adjust the signal coming from the force sensor in the grip of the experimental device, the participants occasionally had some difficulties in satisfying the initial instructions. As a result the sub-maximal efforts were maintained for approximately 10 s in order to be sure to obtain a stable level for 2 s. Therefore, the periods for which maximal and sub-maximal efforts were maintained varied from one participant to the other. The extension of the duration for which the sub-maximal efforts were maintained did not seem to pose any additional problems of fatigue, and in any event, 3-min rest periods between each effort seemed sufficient to prevent any effects of fatigue on the EMGs. Each participant was examined in 36 experimental conditions (3 efforts required in 4 flexion-extension positions of the wrist for each of 3 different pronation-supination positions of the forearm).

After the appropriate preparation of the skin, the EMGs of the flexor digitorum superficialis (FDS) and of the extensor digitorum (ED) were collected using surface electrodes (Blue Sensor®) placed on the forearm at approximately one quarter of the distance from the elbow to the wrist as measured from the elbow (Zipp, 1982). The inter-electrode impedance was less than 5 kΩ. The EMG was then rectified and integrated with a period of 200 ms for 2 s before contraction in order to obtain the EMG for the muscle in a resting state, and then for 2 s—the duration corresponding to either the period of maximal effort, or the first 2 s of stable force in the case of a sub-maximal effort.

The MVC recorded when the wrist was in medium extension ($\approx 30°$) and the forearm in neutral and the corresponding integrated EMGs (see section 3.1.) were used as reference values in order to standardize all of the force data and the EMGs, and, therefore, to be able to present relative values. The integrated EMG was standardized using a procedure adapted from that proposed by Mirka (1994):

$$\mathrm{EMG}(\%) = \frac{\overline{\mathrm{EMG}} - \overline{\mathrm{EMG}}_{\mathrm{rest}}}{\overline{\mathrm{EMG}}_{\mathrm{max}} - \overline{\mathrm{EMG}}_{\mathrm{rest}}}$$

EMG (%) — Value of the standardized EMG;
$\overline{\mathrm{EMG}}$ — Mean value of the rectified, integrated EMG over 2 s;
$\overline{\mathrm{EMG}}_{\mathrm{rest}}$ — Mean value of the rectified, integrated EMG over 2 s recorded while the muscle was in a state of rest;
$\overline{\mathrm{EMG}}_{\mathrm{max}}$ — Mean value of the rectified, integrated EMG over 2 s recorded for the maximal effort used as the reference (see results section 3.1.).

# 3. RESULTS

## 3.1. Maximal Voluntary Grip Force

The mean values and standard deviations of the maximal voluntary grip force (expressed in daN) obtained in different positions of flexion-extension of the wrist and pronation-supination of the forearm of the 15 participants are shown in Table 1.

The highest maximal voluntary grip force was attained when the wrist is in the medium extension position (30°), and the forearm in the neutral one. This position was, therefore, chosen as the reference for

**TABLE 1. Mean Values of the Maximal Voluntary Force Expressed in daN (*SD*) for Different Positions of Flexion-Extension of the Wrist and Pronation-Supination of the Forearm**

| Wrist | Forearm Pronation | Forearm Neutral | Forearm Supination |
|---|---|---|---|
| Maximal extension | 27.9 (5.1) | 31.4 (5.5) | 30.9 (7.4) |
| Medium extension | 28.3 (4.5) | 34.3 (6.6) | 33.3 (6.5) |
| Neutral position | 25.4 (5.4) | 30.1 (4.9) | 30.5 (5.4) |
| Maximal flexion | 18.8 (4.9) | 22.1 (6.9) | 21.4 (6.2) |

standardizing the signals, and all values of force and EMG are expressed in terms of a percentage of the values recorded in this position. The relative values of the grip force and of the EMG are referred to as $force_{rel}$ and as $EMG_{rel}$.

The maximal voluntary grip force was higher when the wrist is in maximal extension than in a position of maximal flexion. Similarly, the maximal voluntary grip force was higher when the forearm was in supination than when it was pronated, whereas the MVCs in neutral forearm position and in supination were not significantly different.

## 3.2. Angles of Flexion-Extension of the Wrist and of Pronation and Supination of the Forearm

The means and standard deviations (in degrees) of all angle values of flexion-extension of the wrist and of pronation-supination of the forearm of the 15 participants are given in Table 2. For the sake of clarity, the angles of flexion of the wrist and of pronation of the forearm are considered as negative, whereas those of wrist extension and forearm supination as positive.

**TABLE 2. Mean Values (in Degrees) and *SD* (in Parentheses) of Articular Positions in the Flexion-Extension Plane for the Wrist, and in the Plane of Pronation-Supination of the Forearm**

| | Pronation | | Neutral | | Supination | |
|---|---|---|---|---|---|---|
| Wrist | Forearm | Wrist | Forearm | Wrist | Forearm | Wrist |
| Maximal extension | 47.6 (11.7) | 43.2 (10.6) | 62.3 (8.9) | 12.3 (8.9) | 62.7 (7.7) | −25.3 (11.0) |
| Medium extension | 13.6 (9.2) | 36.5 (10.4) | 27.2 (6.5) | 10.1 (7.3) | 36.1 (8.9) | −27.9 (9.6) |
| Neutral position | −8.1 (10.1) | 35.6 (10.3) | 5.8 (7.0) | 10.0 (9.1) | 13.5 (9.5) | −29.9 (9.3) |
| Maximal flexion | −40.0 (7.4) | 24.7 (11.6) | −33.4 (8.9) | −3.6 (12.1) | −6.8 (9.7) | −35.3 (8.2) |

In neutral positions of the wrist, the angle values of flexion-extension were initially set to zero degree by means of a rule placed over the hand and the forearm. The change in these values can be explained as follows:

- the wrist slightly extended when the participant squeezed the handle,
- the calibration of the goniometer was affected by the forearm position (Armstrong, Dunnigan, Ulin, & Foulke, 1993).

## 3.3. Influence of the Flexion-Extension of the Wrist and of the Pronation-Supination of the Forearm on the Grip Force, and on the EMG of the FDS and ED

Regardless of the level of force, the flexion-extension of the wrist, and the pronation-supination of the forearm had a significant effect on the $force_{rel}$ ($p < .001$), on the $EMG_{rel}$ of the FDS ($p < .001$), and on the $EMG_{rel}$ of the ED ($p < .001$). The $force_{rel}$ was generally slightly lower in a position of maximum wrist extension than in the reference position (see section 3.1.), and significantly lower in a position of maximum flexion. Furthermore, the $force_{rel}$ is much lower in forearm pronation than in neutral position or in supination. The $EMG_{rel}$ of the FDS showed a maximum value in the reference position. On the other hand, its value was often much lower in the maximum wrist extension than in maximum flexion. The $EMG_{rel}$ of the ED was also the highest in the reference position at 50% and 100% of MVC. At 20% of MVC, the maximum amplitude of $EMG_{rel}$ was observed when the wrist is maximally extended, regardless of the position of the forearm. At 20% of the MVC, the amplitude of the $EMG_{rel}$ of the ED was always much higher than the amplitude of the $EMG_{rel}$ of the FDS muscle, at 50% of MVC, the amplitude of these signals was similar, and at 100% of MVC, the trend observed at 20% was inverted.

## 3.4. Empirical Equations for the Prediction of Grip Force

As the angles of flexion-extension of the wrist and pronation-supination of the forearm had a significant effect on both $force_{rel}$, and on the $EMG_{rel}$ of the FDS and ED, it is possible to derive a relationship between the $force_{rel}$ and the $EMG_{rel}$ for each of the positions studied. In order to account for the phenomenon of agonistic-antagonistic co-contraction, the form chosen to express this relationship was $\text{force}_{rel} = f(\text{EMG}_{rel}$ of the FDS and $\text{EMG}_{rel}$ of the ED). Both for the sake of simplicity, and based on results from the literature (Armstrong et al., 1979), it was decided to use a linear relationship of the form

$$\text{force}_{rel} = a \cdot \text{EMG}_{rel}(\text{FDS}) + b \cdot \text{EMG}_{rel}(\text{ED}) \qquad (1)$$

where $a$ and $b$ are weighting coefficients.

The coefficients $a$ and $b$ varied from .27 to .76, and from .16 to .53, respectively, depending on the positions of flexion-extension of the wrist and pronation-supination of the forearm (see Table 3).



**TABLE 3. Linear Relationships of the Form $\text{Force}_{rel} = a \cdot \text{EMG}_{rel}$ (FDS) + $b \cdot \text{EMG}_{rel}$ (ED), Where $a$ and $b$ are Weighting Coefficients for Positions of Flexion-Extension of the Wrist and Pronation-Supination of the Forearm. The Values of $\text{Force}_{rel}$ and of $\text{EMG}_{rel}$ are Respectively Expressed in Percent of MVC and of Corresponding EMGs Obtained in the Reference Position**

| Position of Wrist and Forearm | $\text{force}_{rel} = a \cdot \text{EMG}_{rel}$ (FDS) + $b \cdot \text{EMG}_{rel}$ (ED) |
|---|---|
| Maximal extension & pronation | $\text{force}_{rel} = .64 \cdot \text{EMG}_{rel}$ (FDS) + $.27 \cdot \text{EMG}_{rel}$ (ED) ($r^2 = .88$) |
| Maximal extension & neutral | $\text{force}_{rel} = .74 \cdot \text{EMG}_{rel}$ (FDS) + $.28 \cdot \text{EMG}_{rel}$ (ED) ($r^2 = .89$) |
| Maximal extension & supination | $\text{force}_{rel} = .76 \cdot \text{EMG}_{rel}$ (FDS) + $.16 \cdot \text{EMG}_{rel}$ (ED) ($r^2 = .73$) |
| Average extension & pronation | $\text{force}_{rel} = .53 \cdot \text{EMG}_{rel}$ (FDS) + $.36 \cdot \text{EMG}_{rel}$ (ED) ($r^2 = .90$) |
| Average extension & neutral | $\text{force}_{rel} = .57 \cdot \text{EMG}_{rel}$ (FDS) + $.45 \cdot \text{EMG}_{rel}$ (ED) ($r^2 = .97$) |
| Average extension & supination | $\text{force}_{rel} = .59 \cdot \text{EMG}_{rel}$ (FDS) + $.48 \cdot \text{EMG}_{rel}$ (ED) ($r^2 = .89$) |
| Neutral position & pronation | $\text{force}_{rel} = .51 \cdot \text{EMG}_{rel}$ (FDS) + $.29 \cdot \text{EMG}_{rel}$ (ED) ($r^2 = .88$) |
| Neutral position & neutral | $\text{force}_{rel} = .53 \cdot \text{EMG}_{rel}$ (FDS) + $.40 \cdot \text{EMG}_{rel}$ (ED) ($r^2 = .89$) |
| Neutral position & supination | $\text{force}_{rel} = .55 \cdot \text{EMG}_{rel}$ (FDS) + $.42 \cdot \text{EMG}_{rel}$ (ED) ($r^2 = .86$) |
| Maximal flexion & pronation | $\text{force}_{rel} = .28 \cdot \text{EMG}_{rel}$ (FDS) + $.41 \cdot \text{EMG}_{rel}$ (ED) ($r^2 = .84$) |
| Maximal flexion & supination | $\text{force}_{rel} = .33 \cdot \text{EMG}_{rel}$ (FDS) + $.53 \cdot \text{EMG}_{rel}$ (ED) ($r^2 = .87$) |
| Maximal flexion & neutral | $\text{force}_{rel} = .35 \cdot \text{EMG}_{rel}$ (FDS) + $.46 \cdot \text{EMG}_{rel}$ (ED) ($r^2 = .77$) |

The coefficient $a$ that weights the $\text{EMG}_{rel}$ of the FDS was higher when the wrist was in extension than when in flexion, whereas the coefficient $b$ that is used to weight the $\text{EMG}_{rel}$ of the ED shows the opposite trend. Similarly, the coefficient a was found to be higher when the forearm was in pronation than when it was in supination. This was also true for $b$, except when the wrist was in maximal extension (see Table 3).

On the assumption that $a$ and $b$ varied linearly as a function of the angles of flexion-extension of the wrist and pronation-supination of the forearm, it was possible to write the coefficients in the following way:

$$a = a_1 \cdot \theta_{f\text{-}e} + a_2 \cdot \theta_{p\text{-}s} + a_3$$
$$b = b_1 \cdot \theta_{f\text{-}e} + b_2 \cdot \theta_{p\text{-}s} + b_3$$

where,

$\theta_{f\text{-}e}$ is the angle of flexion-extension of the wrist, and
$\theta_{p\text{-}s}$ is the angle of pronation-supination of the forearm.

Equation 1 can, thus, be rewritten:

$$\text{force}_{rel} = (a_1 \cdot \theta_{f\text{-}e} + a_2 \cdot \theta_{p\text{-}s} + a_3) \cdot \text{EMG}_{rel}(\text{FDS}) + (b_1 \cdot \theta_{f\text{-}e} + b_2 \cdot \theta_{p\text{-}s} + b_3) \cdot \text{EMG}_{rel}(\text{ED})$$

or

$$\text{force}_{rel} = a_1 \cdot \theta_{f\text{-}e} \cdot \text{EMG}_{rel}(\text{FCS}) + a_2 \cdot \theta_{p\text{-}s} \cdot \text{EMG}_{rel}(\text{FCS}) + a_3 \cdot \text{EMG}_{rel}(\text{FCS}) + b_1 \cdot \theta_{f\text{-}e} \cdot \text{EMG}_{rel}(\text{EC}) + b_2 \cdot \theta_{p\text{-}s} \cdot \text{EMG}_{rel}(\text{EC}) + b_3 \cdot \text{EMG}_{rel}(\text{EC})$$

A multivariable linear regression was used to determine the coefficients $a_1$, $a_2$, $a_3$, $b_1$, $b_2$, and $b_3$ with force$_{rel}$ as the dependent variable, and the independent variables were taken to be $\theta_{f\text{-}e} \cdot \text{EMG}_{rel}(\text{FDS})$, $\theta_{p\text{-}s} \cdot \text{EMG}_{rel}$ (FDS), $\text{EMG}_{rel}(\text{FDS})$, $\theta_{f\text{-}e} \cdot \text{EMG}_{rel}(\text{ED})$, $\theta_{p\text{-}s} \cdot \text{EMG}_{rel}(\text{ED})$, and $\text{EMG}_{rel}(\text{ED})$. An initial analysis showed that the independent variable $\theta_{p\text{-}s} \cdot \text{EMG}_{rel}(\text{FDS})$ was not significant ($p$ = .63), so the value of $a_2$ is zero. The final results are shown in Table 4.

**TABLE 4. Multi-Variable Regression with Dependant Variable = Force$_{rel}$, and the Independent Variables = $\theta_{f-e} \cdot \text{EMG}_{rel}$ (FCS), $\text{EMG}_{rel}$(FCS), $\theta_{f-e} \cdot \text{EMG}_{rel}$ (ED), $\theta_{p-s} \cdot \text{EMG}_{rel}$ (ED) and $\text{EMG}_{rel}$ (ED)**

| Independant Variable | Coefficient | Standard Error | Value of $t$ | Level of Signification |
|---|---|---|---|---|
| $\theta_{f-e} \cdot \text{EMG}_{rel}$(FDS) | $a_1$ = .0045 | .00049 | 9.36 | .0000 |
| $\text{EMG}_{rel}$(FDS) | $a_3$ = .48 | .01955 | 24.78 | .0000 |
| $\theta_{f-e} \cdot \text{EMG}_{rel}$(ED) | $b_1$ = −.0014 | .00053 | −2.63 | .0086 |
| $\theta_{p-s} \cdot \text{EMG}_{rel}$(ED) | $b_2$ = −.0016 | .00026 | −6.23 | .0000 |
| $\text{EMG}_{rel}$(ED) | $b_3$ = .4 | .02192 | 18.25 | .0000 |

*Notes.* Correlation coefficient $r$ = .93, standard error of estimation $\sigma$ = .099.

The empirical relationship that can be used to evaluate the relative grip force can, thus, be written

$$\begin{aligned}\text{force}_{rel} = {} & 0.0045 \cdot \theta_{f\text{-}e} \cdot \text{EMG}_{rel}(\text{FDS}) + 0.48 \cdot \text{EMG}_{rel}(\text{FDS}) \\ & - 0.0014 \cdot \theta_{f\text{-}e} \cdot \text{EMG}_{rel}(\text{ED}) - 0.0016 \cdot \theta_{p\text{-}s} \cdot \text{EMG}_{rel}(\text{ED}) \\ & + 0.4 \cdot \text{EMG}_{rel}(\text{ED}) \\ & r^2 = .86,\ \sigma = .099\end{aligned} \tag{2}$$

From the linear regression between the relative force measured during the experimental tests and the relative force calculated with the empirical relationship (Equation 2), shown in Figure 2, it can be seen that the difference between the measured value and the calculated value is less than 20% for values of $\text{force}_{rel}$ less than 50% of the maximal voluntary force. Above this level, the difference is somewhat greater (<40%).

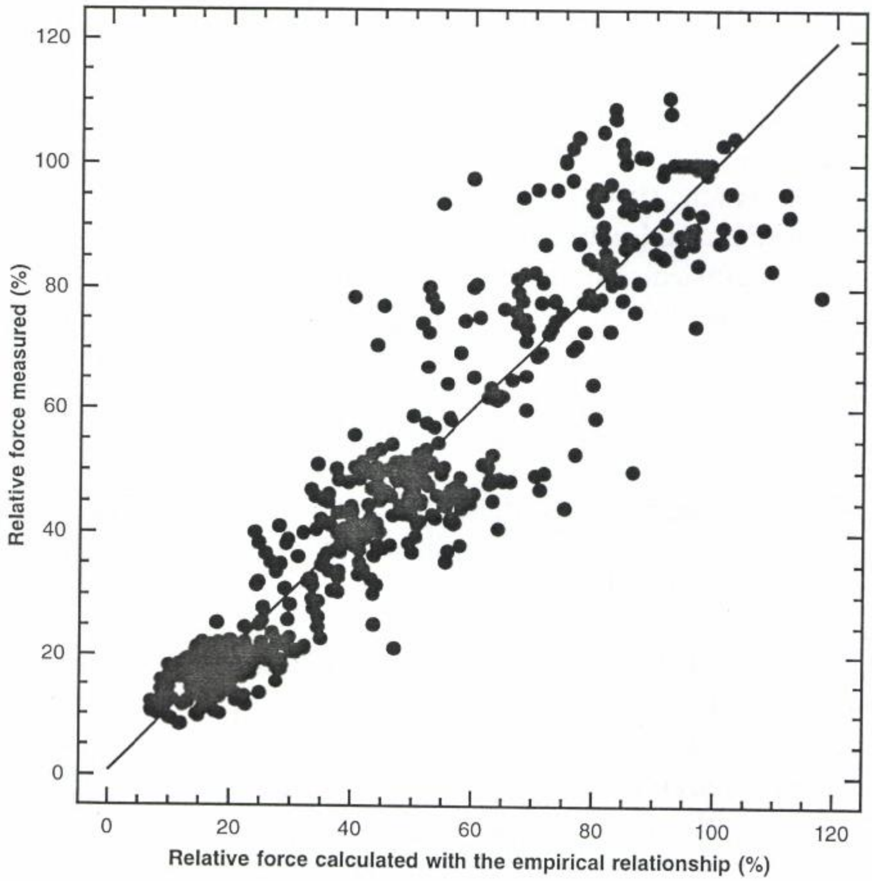


**Figure 2. Results of the linear regression between the relative force measured during the experimental tests and the relative force calculated with the empirical relationship (Equation 2).**

# 4. DISCUSSION

The objective of this work was to study the variation of the grip force and the EMGs of the muscles involved in the action of grasping as a function of different positions of the wrist and forearm, and to find an empirical relationship to evaluate the grip force using EMGs that can be used in ergonomic studies where it is necessary to measure grip efforts.

## 4.1. Physiological Aspects

### *4.1.1. Variation of the maximal voluntary contraction (MVC)*

The highest MVC is observed when the wrist is in medium extension and the forearm in neutral position. This result is in good agreement with the results of Ranaivosoa (1992) and Terrel and Purswell (1976).

The decrease in the MVC from a position of medium extension to one of extreme flexion of the wrist, and from supination to pronation of the forearm is essentially due to a reduction in the length of the FDS (Terrel & Purswell, 1976). On the other hand, the decrease in the MVC between medium and extreme extension of the wrist would seem to be due to a less efficient buttressing force from the thenar and hypothenar eminences (Terrel & Purswell, 1976).

### *4.1.2. Contribution of the different muscles involved in the grip effort to the EMG*

Generally speaking, the results indicate that the extensor muscle is more active than the flexor muscle for slight grip efforts. The ED plays an important role in stabilizing the articulation of the wrist for low levels of force.

On the other hand, the equations presented in Table 3 show that the ponderation of the contribution of the FDS and of the ED to the EMG varies as a function of the position of the hand. Thus, when the wrist is in maximal extension, the activity of the ED is lower than that of the FDS. On the other hand, the opposite of this result is observed when the wrist is in maximal flexion. Similarly, for a given position of the wrist the weighting factors of the EMGs of the FDS and of the ED are generally higher when the arm is in supination than in pronation. Whereas this variation of the different weighting factors might be of physiological origin, the physical nature of the modification of the detection field of the electrodes caused by their relative displacement with respect to the muscle cannot be excluded.

Finally, the weak value of the $a_2$ coefficient indicates that the variation of the EMG of the FDS associated with the pronation-supination of the forearm does not influence the evaluation of the grip force.

## 4.2. Development of the Empirical Relationship

### *4.2.1. Form of the force-EMG relationship*

The relationship assumes a linear relationship between the force and the EMGs of the FDS and ED. Armstrong et al. (1979) also proposed an expression of this form for the relationship between the grip force and the EMG of the FDS muscle. On the other hand, some other authors (Duque, Masset, & Malchaire, 1995; Meyer, Didry, Herrault, & Horwat, 1994; Ranaivosoa, 1992) described curvilinear relationships. However, in some of these cases, the curvature of the force-EMG relationship was very small, and in the present study it was found that the use of non-linear multiplicative or exponential relationships did not significantly improve the correlation coefficients. For this reason, the decision to use the linear form was taken.

### *4.2.2. EMG and forces standardization*

In order to obtain a relationship between the force and the EMGs that is valid for all the participants, it is necessary to standardize these two parameters. The most commonly used method consists in expressing them in terms of values that are comparable from one individual to another: in this case, maximal values. This simple approach becomes more complicated when the maximum used as a reference is obtained under particular conditions that are not necessarily representative of all the conditions. In this study, the maximal force determined in a position of medium extension of the wrist and of neutral position of the forearm was found to be different from that determined with extreme flexion of the wrist and of pronation of the forearm. Thus, it would be necessary to establish a relationship for each position. This solution is obviously complicated, and is contrary to the initial objective of this work, which was to establish a simple relationship. Then all of the force-EMG relationships are based on the maximum maximorum values (Duque et al., 1995; Ranaivosoa, 1992), that is, the maximal voluntary force exerted in the medium extension of the wrist and in the neutral position of the forearm.

## 4.3. Limits of Use

### *4.3.1. Exclusion of abduction-adduction positions of the wrist*

In principle, the angles of abduction-adduction of the wrist should have been taken into account in the empirical expression. Indeed, these positions can influence grip effort (Lamoreux & Hoffer, 1995; Terrel & Purswell, 1976). Nevertheless, it would appear that this influence is especially sensitive at extreme angles, but, at the workplaces this position is quite infrequent, especially in the case of repetitive movements. It was, therefore, decided to avoid complicating the relationship in Equation 2 and not to take these angles into consideration. Thus, in the strictest sense, the empirical relationship cannot be employed when the occupational movements include extreme angles of abduction-adduction of the wrist.

### *4.3.2. Isometric and isotonic contractions*

Given that the force-EMG relationship is only valid for stable muscular contraction, that is, when the level of nervous control remains stable; the length of the muscle does not change, and that there is no fatigue; (Lippold, 1952; Moritani & De Vries, 1978), the empirical relationship (Equation 2) can be used only in isometric isotonic conditions. Even though these conditions are not frequently found simultaneously in practice, this initial step was necessary to evaluate the feasibility of the evaluation of the grip force using an EMG. Nevertheless, it is important to either verify the reliability of this expression when grip efforts are exerted in conditions that differ significantly from the original conditions, or to develop another relationship that is valid under more dynamic conditions. In any event, it would seem that, based on some a priori verification, the model is reliable under quasi-static conditions, that is, when the variation of the length of the muscle and the speed of contraction or elongation remain relatively low. On the other hand, in the case of movements that involve transient phases, the relationship can no longer be used. And, as the movements implicated in CTD often include transient phases (rapid increase in force, rapid wrist movements, etc.), it is, therefore, necessary to use another expression or another method to evaluate the muscular efforts exerted in these cases.

### *4.3.3. Error in the estimation of the force*

The empirical relationship (Equation 2) can be used to evaluate the grip force with an error that can be as high as 40% for high force levels (>50% of MVC; see Figure 2). This error might seem high in absolute terms, but is acceptable to the extent that this essential piece of information is otherwise inaccessible using any other method of observation. Furthermore, the error is lower for forces less than 50% of MVC (<20%).

## 5. CONCLUSION

The results of this study allowed us to define an empirical relationship that linked the integrated EMG of the FDS and ED, as well as the angles of flexion-extension of the wrist and of pronation-supination of the forearm, to the grip force. This linear relationship is easy to use as it requires only one single maximal effort to calibrate it. The standard error of estimation of 9.9% obtained for the elaboration of this expression is less than, or of the same order of magnitude as, those published in the literature. This relationship is valid only under conditions of static or quasi-static contraction (e.g., when a worker uses a hand-held power tool) and does not take into account the angles of abduction-adduction of the wrist. Thus, in the event that the force varies, the speed of the movements involved is no longer zero (or very low), or both, or that the wrist is in extreme angles of abduction-adduction, it is necessary to use other relationships or methods for the estimation of the grip force.

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