A Low-Cost Instrumented Glove for Monitoring Forces During Object Manipulation

Maria Claudia F. Castro and Alberto Cliquet, Jr.

***Abstract*— A rehabilitation program toward restoring upper limb movements based on neuromuscular electrical stimulation (NMES) depends on closed-loop control performance, which has been limited by the development of sensors for practical daily use. This work proposes a system to obtain force feedback. The system is comprised of a Lycra commercial glove with force sensing resistors (FSR's) attached to the distal phalanxes of the thumb, index and long fingers. After amplification and filtering, the signal is digitized through an analog-to-digital (A/D) converter. The polynomial fitting coefficients for the characteristic curves, obtained during the sensor calibration process, were inserted in the software thus enabling the reading of forces exerted during object manipulation. The system was applied to 30 normal subjects in order to verify its feasibility and to acquire knowledge of the normal hand function. Different ways of grasping have been detected according to the *Force versus Time* curve pattern and to the fingers predominantly used in grasping. Results have also shown the influence of parameters such as gender, age, hand size, and object weight in the normal function. The system did show efficacy. It was able to determine grasp forces during object manipulation for up to 73% of the studied sample. This is significant since a single glove was used in a wide range of subjects. For best results in medical applications, the glove should be tailored to the particular characteristics of an individual user.**

***Index Terms*—Force feedback, quadriplegics, upper limb.**

I. Introduction

THE loss of sensory and motor functions involves drastic psychological consequences due to the loss of independence. The restoration of upper limb functional control is a major goal of any rehabilitation program, aiming at maximizing the physical and psychologic potentials of quadriplegics.

In the past 30 years, neuromuscular electrical stimulation systems have been implemented as an important rehabilitation tool to provide a way of activating muscle functions involved in performing movements. The main application of these systems has been the restoration of hand function in patients with quadraplegia due to spinal cord injuries at the C5 and C6 levels. Injuries at these levels generally leave patients with the ability to position their hands in space, but without voluntary grasp control [2], [5], [13], [14], [17]–[21]. The way a patient triggers sequences of stimulation and parameters to generate a variety of patterned sequences of gripping and releasing is tailored to that individual's abilities and needs. Control has usually been achieved by voluntary movements of the opposite shoulder [2], [12], [20], [21] and, more recently, vocal systems have been reported as command source [5], [17].

The main feature of these control systems is that their application must result in stability, repeatability, and regulation of muscle properties under widely different loading conditions, fatigue, and muscle length. For this purpose, closed-loop systems have been developed for feedback regulation of hand function [4], [7], [8], [16], [24]. For automatic regulation of grasp properties, two physical parameters are of central importance: the opening size of the grasp space and the forces exerted on the grasped object. Before contact, no force is exerted by the hand on the object, but position feedback is a variable that can provide information concerning the movement. After contact, force feedback is very important, but position might not be, depending on the compliance of the object. If the object is very rigid, the position feedback would remain nearly constant, due to muscle length and joint angles that remain the same. However, the use of these systems as neuroprosthetic devices for restoration of upper limb function has been limited by the development of sensors for practical daily use.

The types of sensors selected are some of the most commonly used transducers in industrial measurements. However, there are some limitations that prevent their straightforward application [6]. The main criteria for such a system is that the transducers should not affect the normal behavior of the biological system. Therefore, they should be light, small, and easily mountable in such a way as to avoid limiting the range of movement of the limb. In addition, they must be designed so that they can be worn under clothing, be easily attached and removed, and they should not require frequent calibration. Finally, they should not be affected by environments that contain metallic and ferromagnetic materials, electrical noise, and shifts in temperature, lighting, and humidity.

This work suggests an alternative approach for achieving stable grasp force control while performing neuromuscular electrical stimulation. For this purpose an instrumented glove capable of sensing forces at the fingertips is presented along with a custom-made electrogoniometer that monitors elbow angle. The evaluation of the system is based on normal activity studies, thus, allowing for a feasibility study as well as for acquiring knowledge about normal function.

II. Materials and Methods

The monitoring system consists of two transducers: an angular position sensor using an elbow electrogoniometer and force sensors that are part of the instrumented glove.

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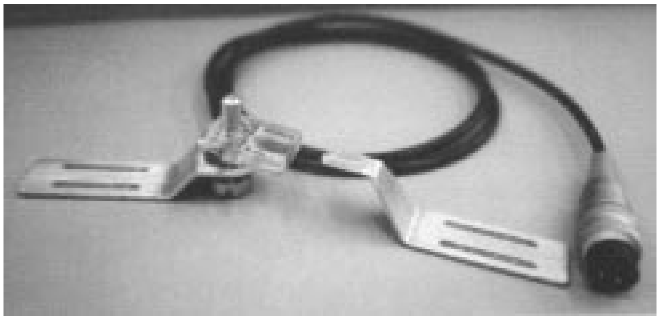

Fig. 1. An elbow electrogoniometer design.

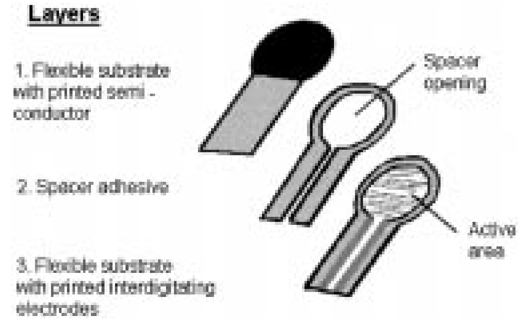

Fig. 2. Force sensing resistor.

They are simple and low-cost devices that follow biomedical requirements for sensors, as mentioned earlier.

An electrogoniometer is an instrument which has an electrical output signal proportional to the angle between two pivoting mounting brackets and is used to record joint angle variations. The elbow electrogoniometer was developed and used as an auxiliary device to determine hand position during object manipulation.

The design of the elbow electrogoniometer consists of two small mounting brackets with a potentiometer introduced at the pivot point (Fig. 1). An arrangement at the joint, shown in Fig. 1, corrects the pivot point displacement that might occur during arm flexion introducing an angular error. Basically, the set-up lets one bracket move translationally with respect to the other without significantly affecting the angular measurement or inhibiting the wearer's movement.

The electrogoniometer was attached to the upper limb through a neoprene elbow pad. In addition, it offers device isolation in such a way that the metallic portions do not touch the subject's arm.

In order to calibrate the system, the elbow electrogoniometer was submitted to static tests, in which the joint angles ranged from -30 to 150°, corresponding to the normal upper limb movement ranges. A characteristic curve was fitted to the calibration data and its coefficients were used with custom made software to provide reliable recording of the elbow angle during object manipulation.

A conductive polymer sensing element (force sensing resistors—FSR) provided by Interlink Electronics [9] was modified to be used as a force transducer. The FSR is a thick-film device consisting of two conducting interdigitated patterns deposited on a thermoplastic sheet facing another sheet containing a conductive polyetherimide film (Fig. 2). A spacer placed between the two plastic sheets permits the two sheets to make electrical contact when force is applied, but otherwise causes the sensor to have infinite impedance in the unloaded state. As the applied force increases, the two layers compress each other, thus, increasing the contact area and decreasing the electrical resistance. The advantages of using such a sensor (Part #300) are its small size ($38.1 \times 7.6 \times 0.25$ mm and 5 mm diameter circular sensing area), low sensitivity to noise and vibration, force resolution (better than 0.5% full scale) and force sensitivity range (<100 g–10 kg) [9]. Additionally, the sensor is durable, thin and flexible, thus making it ideal for attachment to the fingers and hand.

Fig. 3. Instrumented glove design—palmar surface.

Due to the dimensions of the FSR, the exerted force is essentially a point load. The active area is exceedingly small when compared with the contact area between the fingertips and the object. Thus the increasing of the torque at the distal interphalangeal joint that might occur during movement does not affect the direction of force transmission which remains perpendicular. Even so, to improve the sensor's behavior, a method was devised to direct the applied force through the effective sensing area [10]. This was accomplished by placing small plates (1 mm thick) both over and under the sensing area. An adhesive plastic tape was wrapped around each sensor for protection.

The contribution of individual fingers to the total gripping force depends on the grasp pattern used. In a cylindrical grasp, the contributions were larger for the long and index fingers. Also, for all fingers, the distal phalanx exerts the largest force as verified by Amis [1] and Lee and Rim [15]. Based on this information, the FSR's were attached to the distal phalanx of the thumb, index, and long fingers of a Lycra commercial glove, i.e., at the fingertips (Fig. 3). A second glove was worn over the first to provide better adjustment on the subject's hand.

An instrumentation unit including amplifiers and filters was used to condition the output signal and an optocoupler was used to ensure subject safety. The signal was digitized through an analog-to-digital (A/D) converter and visualized graphically using C language-based software. The software used did not allow data visualization in real-time during the experiments. Data collected were stored for later analysis. The selected sampling rate of 40 Hz allows for good graphical

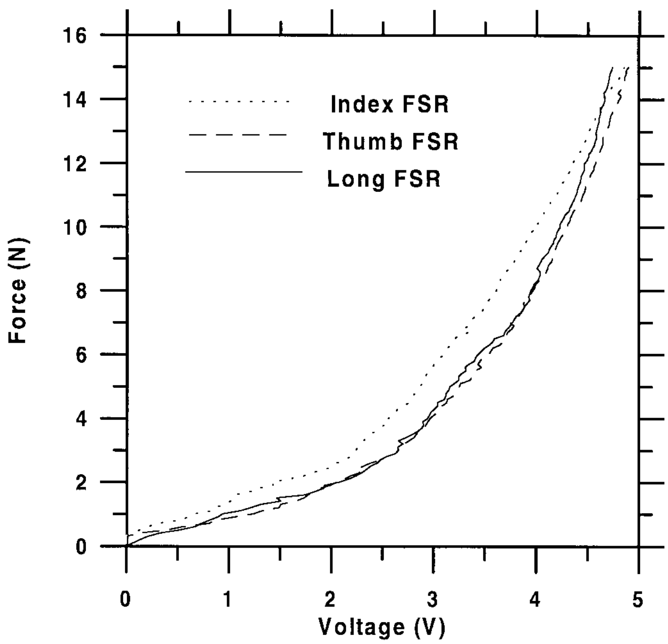

Fig. 4. The instrumented glove characteristic curves.

resolution, and is appropriate for reproduction, visualization, and movement analysis.

In order to calibrate the system, the sensors were submitted to static tests in which normal forces ranged from 0–15 N. Standard loads were transmitted to the sensor's active area through a small (20 mm diameter) sphere in such a way that the force was locally applied. A characteristic curve (seventh order), shown in Fig. 4, was fitted to the calibration data. The fitting coefficients were used in the analysis software, enabling the reading of forces exerted during object manipulation. The experiments showed that there is minimal hysteresis in the system and that the unloading cycle values fall within 6% of the loading cycle measurements.

III. Results

The system was tested on 30 normal subjects (15 male and 15 female with ages between 17–44 years old) to investigate the behavior of the grasping force. The elbow electrogoniometer and the instrumented glove were positioned on the right upper limb (Fig. 5). The subjects had to reach, grasp, and manipulate rigid cylindrical objects as in a drinking task. The objects had the same diameter (81.7 mm), but weights ranging from 2–10 N. This procedure was repeated five times for each weight and for each subject.

The range of weight of the objects and also the grasp model were selected to represent a functional range of grasp forces attained in common daily life activities.

Based on the results, it was verified that the system did show repeatability, which is presented in Fig. 6 for a single subject.

For each subject, a set of five graphs was plotted based on the weight of the object, corresponding to 2, 4, 6, 8, and 10 N (Fig. 7). Each graph shows four curves: an average joint angle variation (among the five acquisitions) provided by the

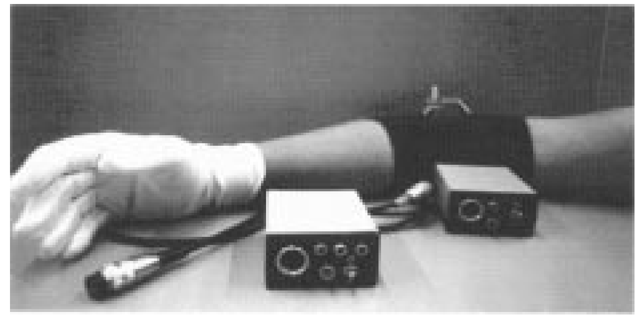

Fig. 5. Positioning of the electrogoniometer and the instrumented glove on the right upper limb.

elbow electrogoniometer and the average forces exerted by the fingers provided by the instrumented glove.

Similarities among the joint angle variation curves can be observed in Fig. 7. The curves are symmetric relative to the maximum arm flexion point. They also presented repeatability for all subjects. They begin with a small angle increase, necessary to reach the object, followed by a larger angle increase for object manipulation to perform the drinking task. The return to the initial position occurs in a similar way.

Comparison between initial and final values, corresponding to arm extension positions, have shown standard deviations smaller than 2° for 98.7% of the subjects. This result shows the efficacy of the electrogoniometer attachment with the joint adjustment system. In addition, the comparison between the maximum value of arm flexion for the same subject within the object weight range showed standard deviations smaller than 2° for 81.8% of the subjects, demonstrating movement repeatability.

Regarding force variation on the fingers, the monitoring system was effective for 73.3% of the events, corresponding to 22 subjects. These subjects presented grasp force patterns that looked similar. The other eight subjects presented some problems. Inappropriate sensor position or an inappropriate glove size, since a single glove was used in a wide range of subjects, resulted in erroneous representations of grasp forces. These subjects did not show the same grasp force pattern for different trials and in some trials the signal of one or more sensors remained null.

Based on the results, different ways of grasping have been detected according to the *Force versus Time* curve pattern and to the fingers predominantly used in grasping. But within the same subject, the same pattern was observed.

Fig. 8(a) shows larger forces being exerted by the thumb and index fingers, characterizing one of the basic models in which grasp force is exerted by the thumb and index fingers, with the long finger being an auxiliary one. This pattern occurred in 68.2% of the evaluated subjects. In Fig. 8(b), the force exerted by the long finger exceeds that of the index finger, thus reflecting a function exchange: the long finger exerts the force with the thumb, while the index acts to assist the grasp.

For both cases, a reasonable plateau is shown during object manipulation, which does not occur on the graphs in Fig. 9. This pattern occurred in 50% of the evaluated subjects. In Fig. 9(a), a force peak associated with the instant of grasping

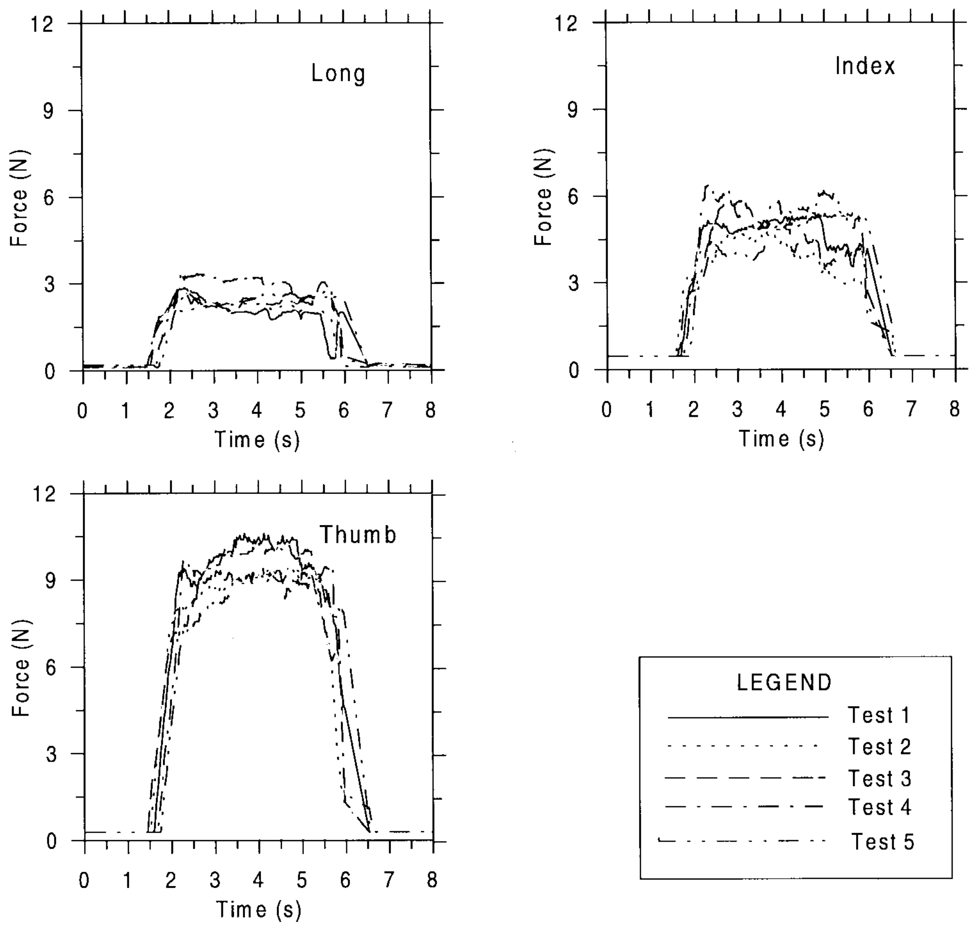

Fig. 6. Curves obtained for a single subject over five trials showing the forces exerted by the fingers while grasping an object of 8 N.

can be noticed. The graph in Fig. 9(b) shows another peak representing the instant when the object is released. Fig. 9(c) shows a smooth decrease of force during object manipulation, therefore, characterizing another pattern.

Results have also shown the influence of parameters such as gender, age, size of the hand, and object weight in the normal function characterization. For this purpose, forces exerted on an object of 8 N at the maximum arm flexion point were used in a variance analysis procedure (ANOVA—$p < 0.01\%$).

Significant differences were observed among the forces exerted on objects of different weights. This relation can be expressed through a linear model at a high level of significance ($\alpha = 5\%$) showing an increase of exerted force with an increase in object weight, for 86.4% of the 22 successfully studied subjects.

Using the same method it was verified that the exerted force is an individual characteristic. The analysis showed significant differences among the forces exerted by different subjects, which are summarized in Table I. The data represent the average of forces exerted by the 22 subjects studied for each object weight. The standard deviations suggested significant differences among forces exerted by each subject.

Within the parameters that can be responsible for this dependence between force and subject, the subject's age seemed to have a considerable influence on the forces exerted by the index and long fingers and the thumb. This was confirmed by ANOVA. A linear regression indicated a tendency toward an increase in grasp force with an increase in the subject's age. But data dispersion does not allow assurance of the relationship between these parameters due to a low correlation coefficient.

With the subject's hand fully opened, the distance between the tips of the long finger and thumb was assumed to be an indicator of hand size. Based on this assumption and on ANOVA, the influence of hand size was significant only for forces exerted by the long finger.

The distribution of forces related to subject gender is shown in Figs. 10 and 11, which show force independence with regard to subject gender. Also, the ANOVA analysis confirmed the assumption of no significant differences between forces exerted by male and female subjects. Fig. 10 shows that forces exerted by male subjects were located more on the extremes of the force range. However, data from female individuals cover almost as wide a force range that is despite the fact that they are predominantly located in the center of the force range. Fig. 11 also shows a homogeneous distribution associated with the thumb force.

IV. Discussion

Increased knowledge of hand position is an important parameter in the functional study of the normal hand, allowing us

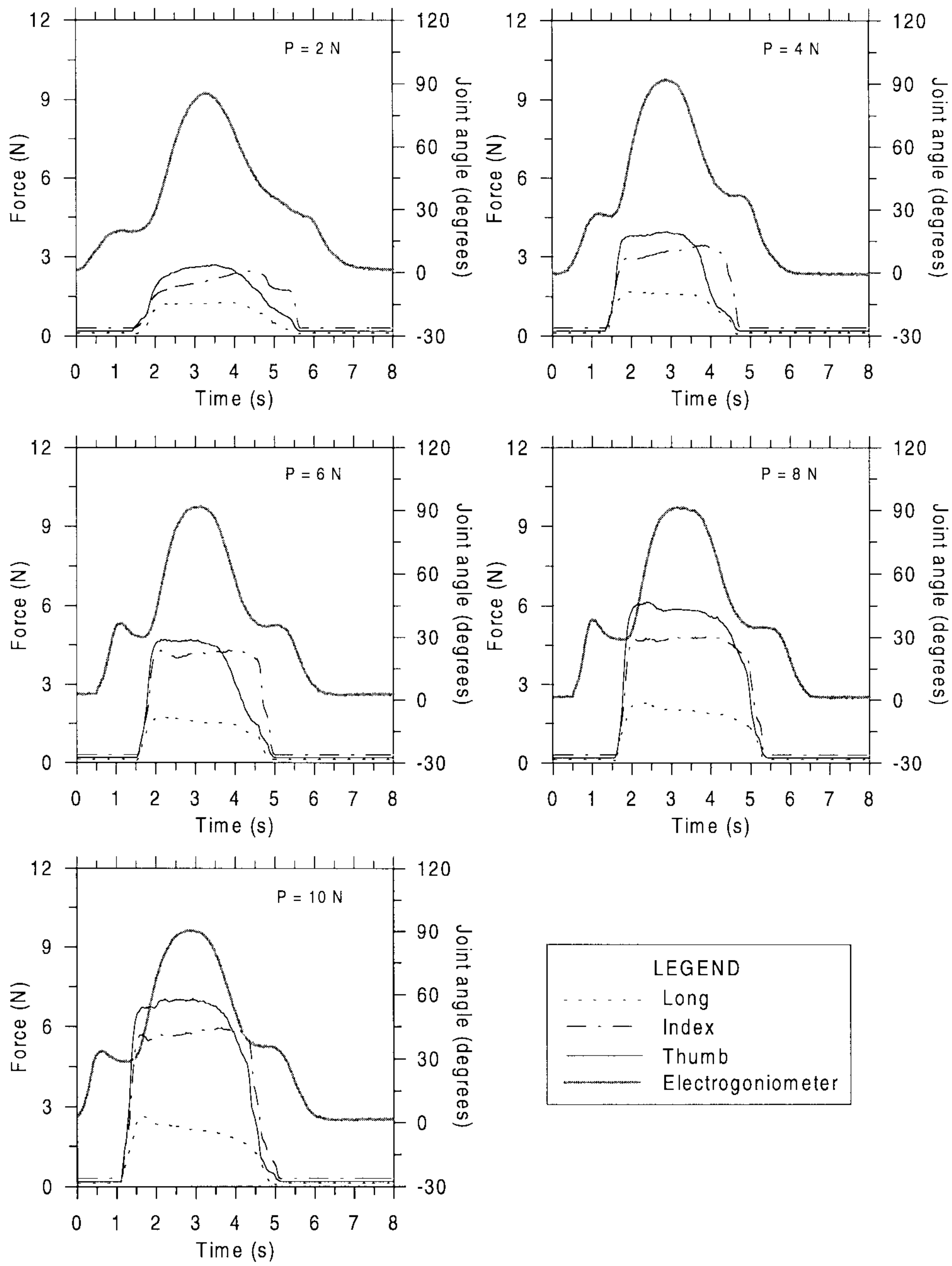

Fig. 7. Typical curves obtained—variation of joint angle and forces exerted by the fingers while grasping objects with weights ranging from 2–10 N.

to detect relationships between grasp force and hand position. The elbow electrogoniometer developed was effective for this purpose, although it might be a redundant parameter in a quadriplegic movement control system when patients are able to position their hands in space (C5–C6). Nonetheless, it can be used as a control parameter since it shows in which phase of the movement the hand is.

Otherwise, force monitoring is essential for a movement performance evaluation. A feedback control system employing a combination of force and finger position feedback can provide grasp regulation under different conditions. The instrumented glove displayed good performance, being able to accurately measure grasp forces during object manipulation for up to 73% of the studied sample. Such a success rate is relatively high considering that a system aimed at a clinical application must be customized for individual users. This is due to the fact that there is a great variation, within the population of persons with quadriplegia, in grasping patterns achieved by neuromuscular electrical stimulation. This customization of the sensor positions and glove size is necessary to ensure optimal performance.

An analysis of the results showed different grasp force patterns which suggest that each person uses a different and specific pattern of muscle activation to accomplish the same task. In a typical drinking task, the index finger was predominantly used. The long finger's contribution to the task was an auxiliary one, mostly improving grasp stability. In most cases, the force exerted by the auxiliary finger remained constant as the object weight increased, indicating that the auxiliary finger's purpose is more closely related to grasp

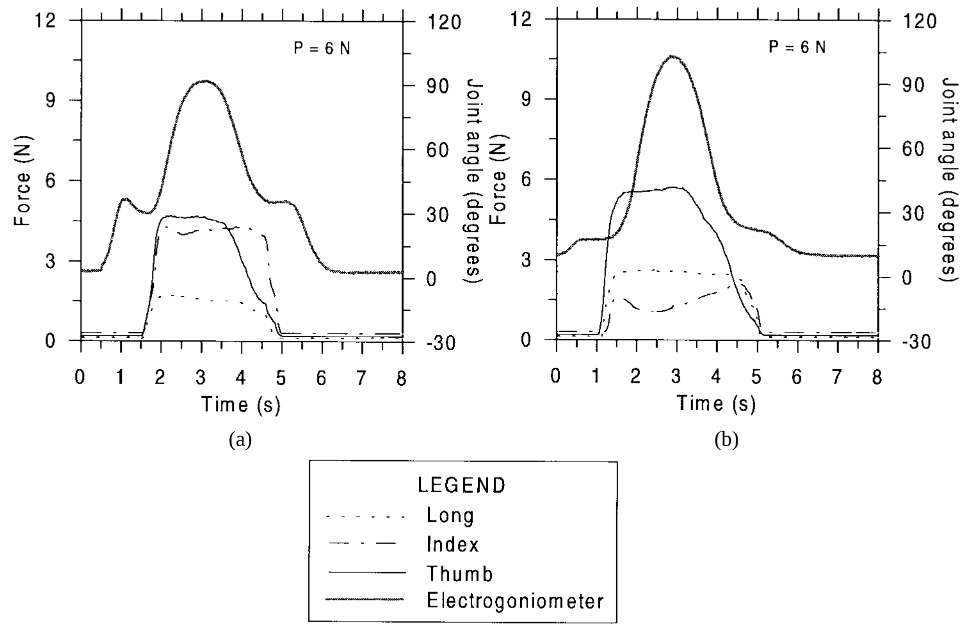

Fig. 8. Forces exerted on an object of 6 N by different subjects showing different patterns of grasping according to the fingers predominantly used.

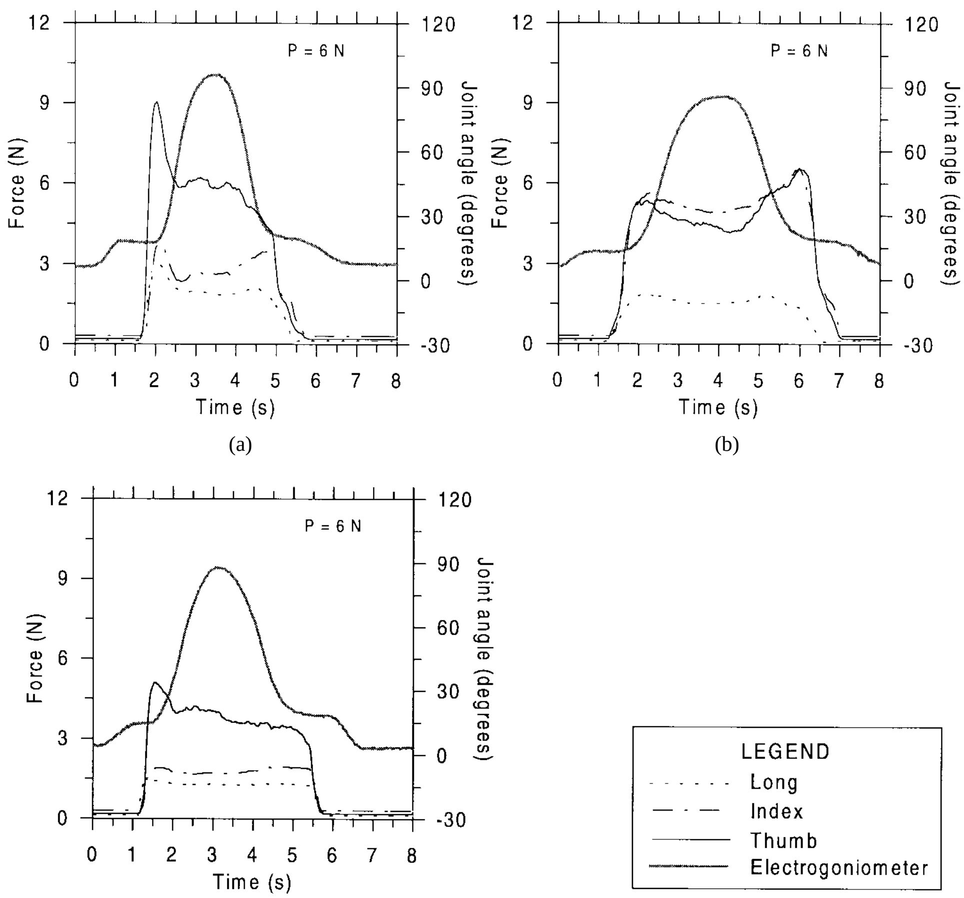

Fig. 9. Forces exerted on an object of 6 N by different subjects showing different patterns of grasping according to the force variations during object manipulation.

stability than to grasp force. According to the *Force versus Time* curves, two statistically equivalent ways of cylindrical grasping have been detected: in the first case, the exerted force is constant during object manipulation; the other pattern shows a peak when the subject reaches the object, followed by a decreasing force. Also, some of these curves show another

TABLE I
VARIABILITY OF FORCE EXERTED AMONG THE SUBJECTS OF THE STUDIED SAMPLE

Object Weight (N)	Force (N) (average ± standard deviation)		
	Long Finger	Index Finger	Thumb
2	1.33 ± 0.41	1.22 ± 0.80	3.16 ± 1.26
4	1.54 ± 0.57	1.73 ± 0.95	4.20 ± 1.23
6	1.74 ± 0.75	2.18 ± 1.28	4.98 ± 1.31
8	1.80 ± 0.71	2.67 ± 1.46	5.54 ± 1.48
10	1.92 ± 0.73	3.05 ± 1.56	5.73 ± 1.99

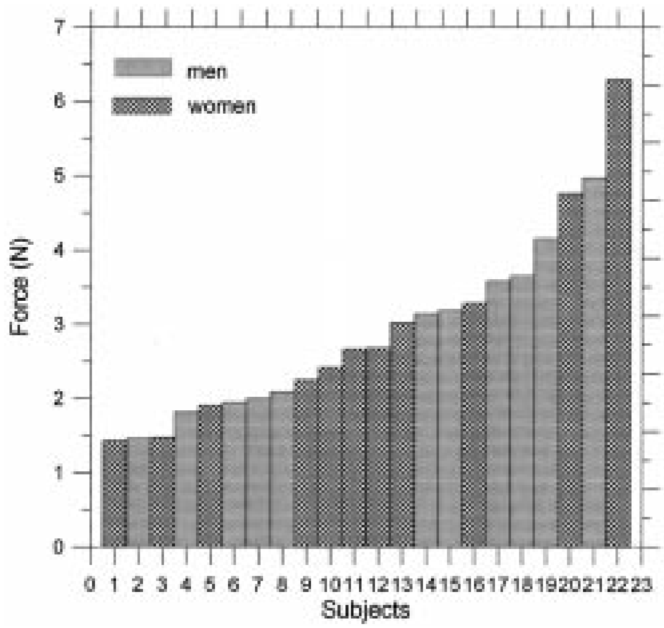

Fig. 10. Influence of subject gender on the forces exerted by the fingers (index or long fingers depending on the grasp pattern).

peak on the instant of release. Burelbach and Crago [3] verified the occurrence of only the second pattern during the drinking task performed through neuromuscular electrical stimulation in quadriplegics. Westling and Johansson [23] and Johansson *et al.* [11] also verified this second pattern, but for a normal precision grip. A larger initial force is necessary to overcome the inertia of the object which was initially motionless. To overcome the inertia of the object during movement, a larger force is also necessary, explaining the second observed peak. During the manipulation task, the biological control system adjusts the force to a lower level at steady-state.

The glove has a significant effect on the forces exerted. Riley *et al.* [22], through comparative studies, detected higher forces associated with glove conditions. A possible explanation is that the glove reduces subject hand sensation, modifying finger tactile receptor responses for the friction between finger and object. The palmar surface of the instrumented glove did not have an antiskidding surface, increasing the chance of slippage. In this case, the forces exerted during the experiments reported here might be larger than the ones typically verified in daily drinking tasks, since normal subjects do not use gloves.

In addition to friction, another parameter which influences the force is the object's weight. The results showed a linear relationship between these parameters, which agrees with the

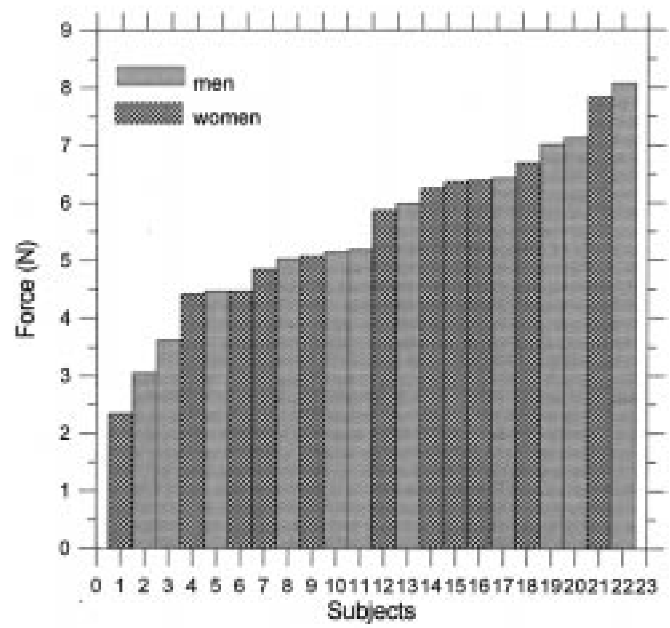

Fig. 11. Influence of subject gender on the force exerted by the thumb.

studies of Westling and Johansson [23] and of Johansson *et al.* [11] in spite of different grasping patterns.

The results showed a correlation between the exerted grasp force and the age and hand size of the subject. The increase in grasp force with age might be explained by loss of tactile sensitivity with aging, although the age range for the present study does not allow assurance of this correlation. The latter parameter influences only the force exerted by the long finger, which is assumed to be, in 68% of the evaluated subjects, an auxiliary function related to movement stability strategies that are individualized.

The force independence associated with gender was expected since the performed task did not involve the maximum forces. Instead, it involved forces normally used for daily activities.

V. CONCLUSION

The exerted force variability for all the subjects confirms that grasp is an individual characteristic, in spite of some basic patterns that were verified. It is suggested that the glove needs to be developed according to the characteristics of each subject, particularly in relation to the position of the sensors and to the size of the glove.

This work was limited to a single situation. However, further experiments should be performed using the glove in different tasks and with users of neuromuscular electrical stimulation. Stimulation and closed loop control strategies must be specific to the user due to his/her particular characteristics.

Based on the results, the instrumented glove presents a promising alternative toward force feedback in a grasp control system. The glove should let us attain a useful system, due to the optimization between stimulation signal, joint angle and grasp force. The use of minimum levels of stimulation to achieve sufficient grasp force for object manipulation will delay the onset of muscle fatigue. Furthermore, it is a low-cost system that is cosmetically acceptable and easy to use, thus being appropriate for practical daily use.

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Alberto Cliquet, Jr., for a photograph and biography, see p. 39 of the March 1997 issue of this TRANSACTIONS.