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A force-pressure interface for muscle strength evaluation

Uma interface força-pressão para a avaliação de força muscular

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Abstract
This study considers the development a dynamometer for measuring isometric forces generated on specific muscle strength test: the handgrip test. The model of prehension is characterized by no action of the thumb (power grip). The design, construction and an application of a specific interface based on the mechanical characteristics of a metal diaphragm linked to pressure sensors by a hydraulic system for muscle strength evaluation is presented. The interface is assembled by a diaphragm with a piston in its central area, held inside the device with its edge clamped rigidly. Calibration tests were performed using a Materials Testing Machine (Instron) and the linearity of the voltage output (0-5 V) for the upscale and downscale loading (0-15 kgf) was verified with a correlation coefficient of 0.98. The hysteresis of the diaphragm-based hydraulic devices, describes a constant difference between curves. The results obtained showed the feasibility of utilizing the device in handgrip tests. Thus, a handle was constructed in polystyrene, whose shape accords with the "power-grip" position of the hand. A system has been assembled, consisting of a PC-based hand dynamometer fitted with the hydraulic devices, linked to an ergonomic chair. An 8-channel programmable signal-conditioner recorder provided the adequate amplification of analog signals from the sensors that were collected by a software system for monitoring and controlling the Analog-to-Digital data acquisition board. In an early test of the hydraulic system, a subject was seated in a standardized position and was instructed to squeeze the dynamometer as hard could as possible during five seconds, in an isometric effort. After recording data, our system can be used in a first moment as a qualitative tool for analysis, permitting a comparison of force-time curve shapes among each finger. Therefore, the importance of this work is demonstrated by the advantage of the system to identify the fingers' contributions to the handgrip. However, additional research on how the total handgrip is affected by fingers action have been developed.

Keywords: Metal Diaphragm, Handgrip, Muscle Strength, Hand Dynamometer, Isometric Effort

Resumo
Este estudo considera o desenvolvimento de um dinamômetro para a medição de forças isométricas geradas em teste de força muscular específico: o teste de preensão. O modelo de preensão é

*caracterizado pela ação inibida do polegar (*power grip*). O projeto, a construção e uma aplicação de uma interface específica são apresentados, baseados nas características mecânicas de um diafragma metálico, ligado a sensores de pressão dentro de dispositivos hidráulicos, para a avaliação da força muscular. A interface é composta de um diafragma com um pistão fixado em sua área central. A borda do diafragma é rigidamente engastada dentro do dispositivo hidráulico. Os testes de calibração foram executados através de uma máquina de ensaio de materiais (Instron), quando verificou-se a ocorrência de linearidade (r = 0,98) entre o sinal de saída (0-5 V) com a carga aplicada (0-15 Kgf), a valores crescentes e decrescentes. A histerese para cada dispositivo descreveu uma diferença constante entre as curvas. Os resultados obtidos mostraram a possibilidade de aplicação dos dispositivos em testes de preensão. Uma empunhadura foi construída em poliestireno, cujo formato possibilitou o posicionamento da mão em* power grip. *Um sistema foi, então, montado, consistindo de um dinamômetro ligado a um microcomputador. Um registrador de oito canais proporcionou a adequada amplificação dos sinais analógicos de saída dos sensores, os quais são armazenados e processados em computador, após a conversão A/D. Num teste preliminar, um indivíduo sentado em posicionamento padrão foi instruído a executar, durante cinco segundos, esforço máximo de preensão. Após a aquisição dos dados, este sistema possibilita a análise qualitativa no sentido de permitir a comparação das formas das curvas força-tempo entre cada dedo. Portanto, a importância deste trabalho é demonstrada pela vantagem do sistema proposto identificar as contribuições individuais dos dedos à força de preensão total.*

Palavras-chave: *Diafragma metálico, Dinamômetro, Esforço isométrico, Força muscular, Preensão*

Introduction

The measurement of the force developed during voluntary muscle contraction has long been used in many areas, including orthopaedics, rehabilitation engineering and physiotherapy. Measuring devices have ranged from mechanical dynamographs to strain gage sensors.

As exercise is a combination of rhythmic contractions and static effort, specific devices should be used to assess muscle strength. This study considers the isometric forces generated on dynamometers designed for specific muscle strength test: the handgrip test. The major problem was to design a dynamometer that prevents the use of some part of the body weight as a lever to generate force (Lind, 1983). Some of these instruments are now easily available and others are specifically designed for laboratory research (Marino and Gleim, 1984). On the other hand, the quantitative isometric force measurements can be useful for hand therapists to determine the presence and extent of weakness and to form the baseline for therapeutic procedures (The National Isometric Muscle Strength Database Consortium, 1996) and improve the electrodes positioning and muscle artificial stimulation, to diminish an inadequate flexion of joints and improve hand function in people with spinal cord injury (Prochaska *et al.*, 1997).

In addition to being an economical measure that is easy to administer, data on the handgrip strength of normal subjects have already been presented using many devices, the most working through strain gage application. An example is the use of two metal beams separated and fastened at the base to form a tuning-fork structure with an application of strain gages to provide strain readings as the beam is bent by the grasp action (An et alii, 1980; Helliwell *et al.*, 1987). Another application of strain gages is presented by Pronk and Niesing (1981) with a handgrip dynamometer designed for measurement the strain in shearing stress way, with the use of a I-shaped beam. Nevertheless, Patterson and Gabbard (1982) suggest that the hydraulic transducer is more sensitive to changes in force than is the lever-type dynamometer. Their device consists of a pressure transducer assembled with a cylindrical; reinforced air hose. Among that electromechanical dynamometers specially designed for the laboratory set, there are some instruments that are commercially available for clinical use. We can mention the Jamar™ dynamometer and the Martin vigorimeter as well-known and frequently used devices for clinical and experimental procedures (Desrosiers *et al.*, 1994). In most of these instruments, only maximum strength was evaluated and the device used, the Jamar dynamometer, considered as the most precise instrument for measuring grip strength (Mathiowetz *et al.*, 1984) was projected for predetermined functions, and therefore was not reliable for assessment of other muscle groups.

On the other hand, researchers have developed some systems to analyse the information gathered on the tests over time. Helliwell *et al.* (1987) suggested that the rate of development of maximum grip was a more sensitive indicator of hand dysfunction than the maximum grip strength itself. An alternative for more consistent measure than time for endurance in isometric bouts should be the area under force-time curves (Byrd and Jenness, 1982). Another force-time characteristics could be drawn from the studies of Smith *et al.* (1989) and Chengalur *et al.* (1990) when the investigation explored the sincere and feigned maximal grip forces, considering the peak force, average force and variance to determine several discriminator variables. Lindahl *et al.* (1994) as Helliwell *et al.* (1987) evaluate the force-time curves from discrete parameters, as the maximum grip value, the time to maximum grip and the rate of loss of grip from maximum value to point of release.

However, any evaluation used to measure muscle strength must be reliable and valid. This is normally achieved by the use of standardized positioning and instructions (Daniels and Worthingham, 1980; Kendall and McCreary, 1983). Special problems arise when a unique sensor or device has to be used in different muscle tests. As a device, its construction is based on a pre-determined function, which renders it not reliable for other uses, unless the meter is removed and replaced with a force transducer. As a sensor, a specific mechanical attachment is always necessary. In both cases, no mechanical interface to provide the proportionality of the response to the applied muscular force has been reported.

In this work, a specific interface is described based on the mechanical characteristics of metal diaphragms (Measurements Group, 1982; Naca, 1938; Naca, 1942) linked to pressure sensors by a hydraulic system. It uses strain-gage based pressure sensors, that presents obvious advantages over other conventional devices: they are small, designed to have the usual transducer requirements of linearity and reproducibility; and their electrical output can be linked directly to an analog-to-digital board in a microcomputer (Jain *et alii*, 1985). The use of alternative sensors employing a fixed mechanical system or cantilever beams was avoided for not presenting the same versatility for adaptation to different groups of muscles or different tests.

The system presented here consists of interchangeable modular parts (hydraulic system), to give maximum flexibility allowing different uses with the same transducer, independently of the variation of the applied load. Some theoretical considerations are presented, supported by results from previous studies of handgrip on the diaphragm's capacity to withstand prehension strength (Mazer *et al.*, 1991; Novo Jr. *et al.*, 1994; Novo Jr. *et al.*, 1997). As an important function of the upper limbs is grasping and manipulating objects, the present device is useful for evaluating grasp performance, when neuromuscular electrical stimulation is used towards restoring hand function in spinal cord injury patients (Castro *et al.*, 1997), since provides individual finger forces identification and force-time curve recording for posterior statistical analysis. It is important to mention that the model of prehension for handle design is defined by Kapandji (1970), named as "power grip" with no action of the thumb.

Theoretical Considerations Underlying the Diaphragm Design

Firstly, some concepts are considered. A transducer, for instance, is understood as a device that transforms one type of energy into another. The authors concern themselves here with a specific class of transducers: devices that transform an input of mechanical energy into equivalent electrical signals (throughout strain measurements of sensing elements), for measuring and/or controlling input phenomena. This type of electromechanical transducer is usually located at the source of the physical force or energy, and responds to its magnitude (The Technical Staff, 1988).

The authors only consider static forces, which arise from the action of a fluid on a surface (pressure P) that can always be effectively expressed in the form of an integral of P over the surface S. According to Doebelin (1990), a hydraulic system must be designed with high impedance (interface) to the applied force as shown in Figure 1.

Energy transfer requires the specification of two variable quantities for its description: force and pressure. When these two signals are identified, one can define the generalized input impedance Z as the relationship F/P. While it is usually desirable that a force-measuring device have the greatest possible stiffness, this criterion is not correct for this particular application. The reason is that the presence of the diaphragm inside a clamping module (as will be described later) causes a distortion of the pressure field if diaphragm stiffness is either higher or lower

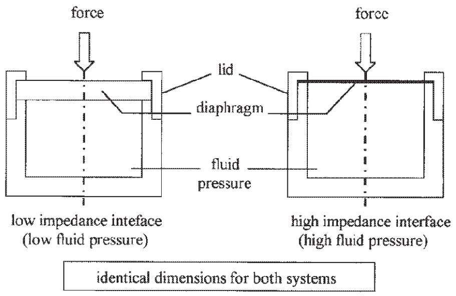

Figure 1. For the same magnitude of applied force, the system with the diaphragm of lesser thickness provides a greater sensitivity.

than the stiffness of the force applied to the piston. That is, a very stiff diaphragm will read too high when an external load is applied, since the lid will compress more than the diaphragm; thus the diaphragm carries a disproportionale share of the total load. Similarly, an excessively pliant diaphragm will read too low a pressure. The best diaphragm is one whose stiffness matches that of the lid in which it is fixed and thus does not distort the pressure field in the sensor.

Therefore, the hydraulic device was mounted at the same time as the output readings of the sensors were been monitored, allowing a minimum of pre-loading effect corresponding to an output range of 1 to 1.5 volts, avoiding saturation of the amplified signals sent to the A/D board.

In this paper, interface is defined as the metal diaphragm where force is applied. The interface will transform force into pressure. Obviously, the magnitude of the fluid pressure will depend on both the force F, and the effective surface in contact with the fluid/thickness of the diaphragm.

The type of interface considered in this work is one which has a deformable fluid-tight surface, as shown in Figure 2a, where a piston receives and aligns a force perpendicular to the diaphragm. However, the force becomes more difficult to calculate because the surface area, $S=\Delta F/\Delta P$ is not immediately known, as in the piston system in Figure 2b. In both cases, change in the applied force (ΔF) causes a variation in fluid pressure (ΔP).

A variety of factors must be taken into account in the design of a diaphragm and identification of surface area (Timoshenko, 1940; Guillon, 1969; Considine, 1974; Measurements Group, 1982): **1)** diameter of the shell (mm); **2)** thickness of the metal (mm); **3)** shape of the corrugations; **4)** number of corrugations; **5)** modulus of elasticity (Pa); **6)** diameter of the piston (mm); **7)** pressure range of the sensor (Pa).

From these factors and the situations of the diaphragm subjected to the conditions shown in Figure 1, the concept of Effective Surface can be derived.

Defined as

$$S_e = \frac{\Delta F}{\Delta P} \tag{1}$$

the Effective Surface (S_e) is an area kept in equilibrium by force ΔF when acted on by pressureΔP. Whereas deformation of the diaphragm is quasi-constant owing to the incompressible fluid, this interface yields force ($S_e.\Delta P$). The calculation of such a force is not straightforward. Whereas, considering the deformation of the diaphragm the effective surface $S_e = V/x$. This means that, if x is the displacement of the center of the diaphragm, V is the volume of the fluid displaced when a pressure P is acting. Simultaneously, a force F balances equally that pressure. So, the equation (1) gives, over the total surface:

$$S_e = \frac{\Delta F}{\Delta P} = \iint_{(s)} \lambda dS \tag{2}$$

where dS is an element of area of the diaphragm and λ is a function of the position of the element on the diaphragm, normally between 0 and 1.

In a first approximation, effective surface area is given by GUILLON (1969):

$$S_e = \frac{\pi}{4}\left[\frac{D_o + D_i}{2}\right]^2 \tag{3}$$

where D_o is the outside diameter (of the casing) and D_i the inside diameter (of the piston), as shown in Figure 2a and Figure 5.

The interface must have a behavior approaching a linear relationship between the force applied to the pressure measured by the sensor, over as wide a range as possible with a minimum hysteresis and permanent zero shift.

There are two possibilities for measuring the force, using either corrugated or uncorrugated diaphragms. Corrugated diaphragms are constructed to allow for their complete expansion.

In our case, owing to the incompressibility of the fluid, a flat diaphragm is used because it has maximum sensitivity to even very slight motion (Measurements Group, 1982; Considine, 1974) but the relationship

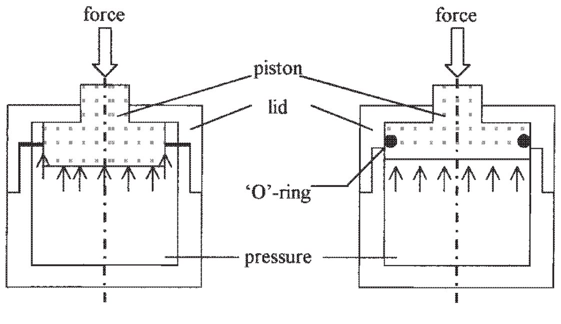

Figure 2. a) Piston-diaphragm arrangement, b) Piston with O-ring.

between force and diaphragm deflection is nonlinear. Acceptable linearity can be maintained by limiting the center deflection (*dd*) of the diaphragm so that it does not exceed its own thickness (*t*) (Dally and Riley, 1991).

Based upon small-deflection theory, maximum diaphragm deflection is given by the following formula (Timoshenko, 1940):

$$d_{max} = K.\left[\frac{P.D_o^{\ 2}}{4.E.t^2}\right] \tag{4}$$

where: d_{max}= maximum deflection (mm); P = maximum pressure of the sensor (Pa); D_o = outside diameter (mm); E = modulus of elasticity (Pa); t = thickness of the diaphragm (mm); K = diaphragm constant.

Considering the use of the diaphragm as shown in Figure 2a and the maximum pressure range of the sensors of 1700 kPa (170 N/cm^2), the d_{max} value is 2.13 x 10^{-9} m. This extremely low deflection is ensured by the incompressibility of the hydraulic fluid, which maintains a linear deflection-pressure relationship as stated by Timoshenko (1940), assuring that (d_{max}/0.03 D$_o$) < 0.0025. Considering the strain distribution over a flat diaphragm, the circumferencial strain is always positive and assumes its maximum value at the center. Otherwise, the radial strain is positive in some regions but negative in others and assumes its maximum negative value at its edge.

On the other hand, when the central region of the diaphragm is stiffened (by the use of a piston, in our case), the circunferential strain vanishes significantly and as a consequence, the radial strain plays an important role in order to increase the effective surface.

The Hydraulic Device

Figure 3 shows a small case (of aluminum) that houses a pressure sensor (for details see appendix). The reduced dimensions are justified by its utilization in a handgrip dynamometer. A metallic diaphragm is rigidly held in place by clamping metallic parts 4 and 8, as shown in Figure 4, where a fluid transforms the force applied to the piston into pressure on the sensor.

The diaphragm

The diaphragm was constructed with 3003-H14 Al-alloy (Belmetal Ind. e Com. Ltda., Brazil) , constant of elasticity E=69x10^9 Pa and thickness of 0.30 mm, as shown in Figure 5. This aluminum alloy was chosen because its commercial availability is greater than steel alloys of low thickness. The temper designation (H14) indicates that the aluminum alloy was strain hardened in order to obtain the desired strength without additional thermal treatment (H1). The digit 4 following the H1 indicates the degree of strain-hardening, i.e., the amount of cold work performed: material with tensile strength halfway between soft and full hard, as stated by LYMAN (1985).

For this Al-alloy, the constant K is equal to 0.00077 corresponding to Poisson’s ratio n = 0.3 and D_o/D_I = 1.22 (Timoshenko, 1940) resulting in an effective surface area of 0.7854 cm^2 with D_o = 11mm and D_i = 9 mm. Thus, the maximum force applied to the piston must equal maximum pressure withstandable by the sensors (as specified by manufacturer), respectively F_{max} = 133.52 N and P_{max} = 1700 kPa or 170 N/cm^2. These values are of sufficient magnitude for measuring individual finger force in a handgrip test.

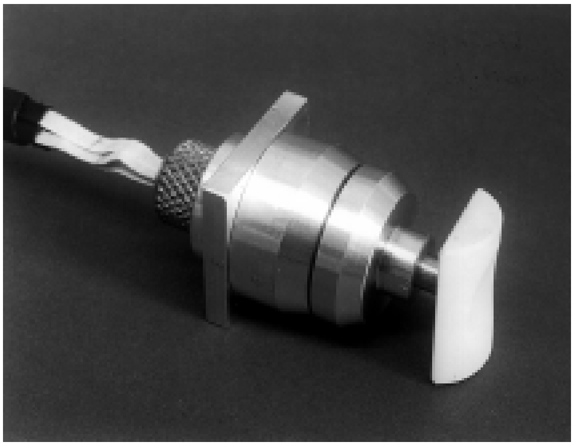

Figure 3. The hydraulic device.

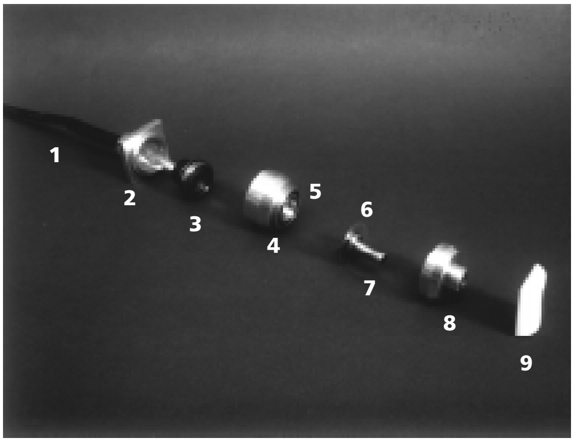

Figure 4. The mobile parts of the hydraulic devices: 1-cable, 2-base, 3-pressure sensor, 4-body, 5-O-ring, 6-diaphragm, 7-piston, 8-lid, 9-finger pad.

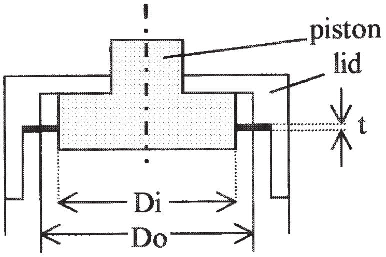

Figure 5. The dimensions of the piston-diaphragm arrangement: D_o = outside diameter; D_i = inside diameter (piston); *t* = thickness of the diaphragm.

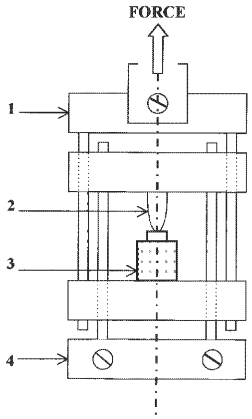

Figure 6. The tension-compression sliding apparatus in the Instron machine: **1**) beam with upward force application, **2**) force transmitter, **3**) hydraulic device, **4**) base.

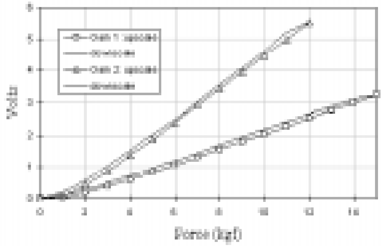

Figure 7. Graph of hysteresis from 0 to 5 V for one hydraulic device (*r* = 0.98). The dashed line indicates the highest level of force/voltage difference.

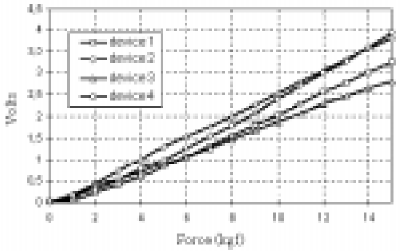

Figure 8. Upscale readings for the hydraulic devices (r=0.98).

Calibration Procedures

Each hydraulic device, adequately sealed and fitted into the dynamometer assembly, was positioned in the INSTRON Machine (model TTDML, 3241 series, Lab. of Materials Tests, Dept. of Materials Engineering, EESC-USP, São Carlos/SP/Brazil) with a specific apparatus for loading as shown in Figure 6.

The hysteresis of each device was observed for data from voltage obtained by 1 kgf increments of the Instron beam at 0.01 cm/min driving the upscale readings to 15 kgf, or until an output of 5 volts. The Instron beam displacement was then inverted, and the output signal decreased progressively, reaching 0 volt. In Figure 7 one of the devices is considered, whose maximal input hysteresis was calculated based on the greatest force/voltage difference (dashed line): 11 kgf for gain 1 and 11 kgf for gain 2. Differences of 0.14 and 0.21 volt were observed between the curves, equivalent to 6.1 and 4.2%, respectively.

Since the response of each hydraulic device to the applied load depended on the sealing processes, the authors aimed to verify if the linearity of response could occur independently of the fit between its parts. It was observed that the harder the diaphragm was clamped, the faster the output signal was saturated. This fact causes a pre-loading of the sensor with no external force applied to the piston. Hence, the slope of the calibration curve increase and the linear region is restrict to a narrow range of force variation. This behavior does not enable the application of high level of force because of the output voltage reaches rapidly its maximum allowed value (for adequate sensor operation). In any case, the relationship load-voltage was sufficiently linear, as shown in Figure 8. The output range (0 - 5V) was necessary because of A/D board configuration for signal conditioning and software management for recording data.

The Instrumented Handle and the Laboratory Set

Figure 9 shows the dynamometer assembly equipped with an anatomic handle providing "power-grip" (Kapandji, 1970), permitting the finger action while excluding the thumb.

Basic principles of ergonomics (Tichauer and Gage, 1977; Grant, Habes and Stewart, 1992) were used in developing this handle, made of polystyrene: **1)** during hand prehension, its length exceeds hand width; **2)** sharp edges were eliminated.

For the present study, a system has been assembled, as shown in Figure 10, consisting of a PC-based hand dynamometer fitted with hydraulic devices, linked to an ergonomic chair. An 8-channel programmable signal-conditioner recorder provides adequate amplification of analog signals from the sensors that are then collected by a software system for monitoring and controlling the Analog-to-Digital data acquisition board.

In an early test of the hydraulic system, a subject was seated in a standardised position as shown in Figure 11a and instructed to squeeze the dynamometer as hard could as possible during five seconds, in an isometric effort. Figure 11b shows a typical force-time curve for the test.

The hysteresis of the diaphragm-based hydraulic devices describes a constant difference between curves. The cause of this kind of hysteresis is mechanical owing to the intrinsic accommodation of the mobile parts of the Instron beam apparatus.

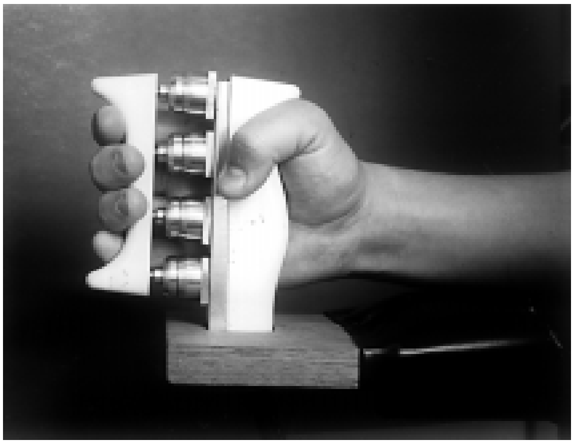

Figure 9. The handle in use: the posterior aspect supporting the thenar eminence and the anterior aspect for finger support.

Figure 10. Laboratory instrumentation for handgrip tests

For upscale readings in particular, the system proves applicable for muscle strength evaluation, through the use of handgrip tests.

These hydraulic devices equipped with anatomic handles are currently being developed for handgrip tests in association with heart rate measurements with wide application, in Rehabilitation Engineering and Exercise Physiology, by studies in cardiovascular adjustments for isometric effort and muscle fatigue indexes.

The hydraulic device's main distinction is that the force is measured through the pressure sensors. It is easily calibrated and can be used for a wide range of force magnitudes, as long as adequate diaphragm is used.

Considering that some studies developed a microcomputer-based system to register the maximal total force of the whole hand, our system can be used permitting a comparison of curve shapes as shown in Figure 12. Therefore, the importance of this work is demonstrated by the advantage of the system to identify the fingers' contributions to the handgrip. For this task, the anterior aspect of the handle showed in Figure 9 is removed and the finger pads (Figure 3 and 4) are used to enabling the individual finger

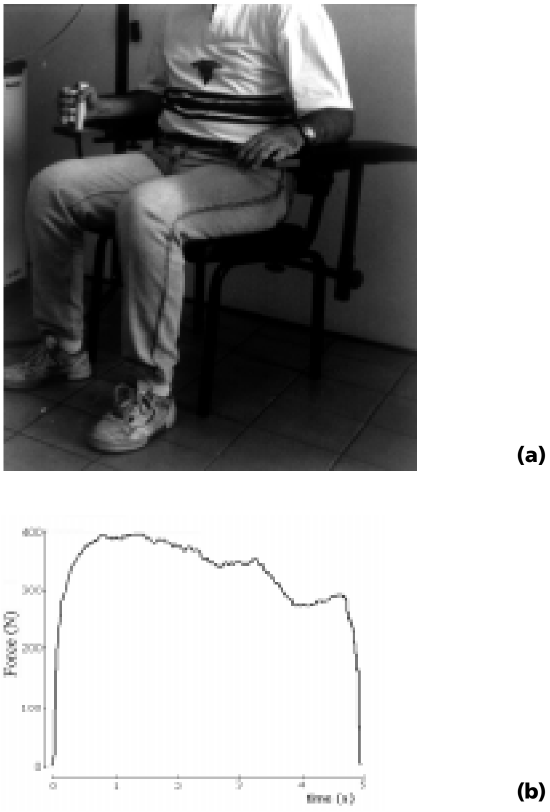

Figure 11. a) Standard position, **b**) Typical force-time curve for the handgrip tests.

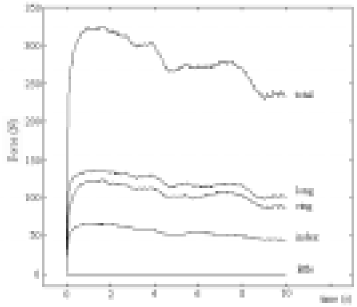

Figure 12. Force-time curve and the individual contributions of the fingers.

support. For example, Figure 12 show us the null contribution of the little finger because of the hand size of the subject is smaller than the handle width. In addition, the feature we can observe is the effective participation of the long and the ring finger than the index finger. Thus, as a qualitative analysis, the use of our system for measurement of individual finger strength can be useful for diagnosis of hand dysfunction.

Additional research on how the total handgrip is affected by fingers action have been developed. In particular, it may be necessary to identify the mechanic-physiological components of the isometric efforts through mathematical modelling in order to interpret the results of tests of normal individuals.

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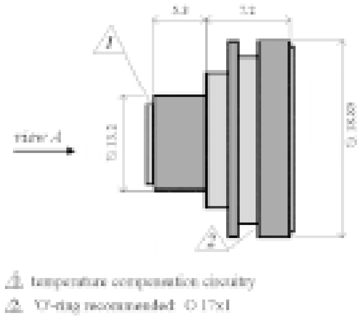
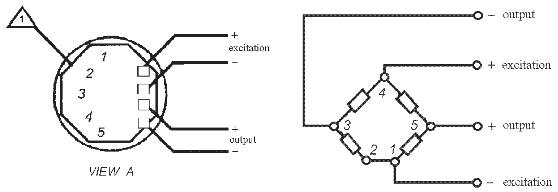
Appendix

This appendix presents details of the pressure sensor model NPI-19A-172-GH (Manufacturer: SODMEX Indústria e Comércio de Materiais de Extensometria Ltda./Brazil)

Dimensional Drawing



Specifications



Technical data

Capacity	170 N/cm^2
Bridge impedance	5000W ± 20% (25 ^{0}C)
Non-linearity	0.10 ± 0.25% FS
Thermal hysteresis	0.10 ± 0.20% FS
Recommended excitation	1 mA
Safe excitation	1.5 mA (máx)
Safe overload rating	200%
Output voltage	100 mV
Operating temperature range	-40 ~ 125 ^{0}C
Accuracy	0.001% FS