

# Development and application of a hand force measurement system

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## Abstract

This presentation describes a system that has been developed by our group for the measurement of hand contact force. The system incorporates 16 to 20 thin profile conductive polymer pressure sensitive resistors attached to a thin athletic grip glove to cover the pulpar regions of the phalangeal segments and palm that contact the grasped object. The electrical responses of these sensors have been found to be linear when calibrated against applied force distributed over the sensor surface area. We have constructed a custom power supply and amplifier module to provide excitation and an adjustable gain to scale all sensor outputs for compatibility with a  $\pm 5V$  analog to digital data acquisition board. Through linear regression the voltage output of each sensor is calibrated against the applied thumb force measured on the load cell. Linearity between applied force and voltage output of the sensor is high, typically in the range of  $0.986 < r^2 < 0.995$ . The studies to date using this system have illustrated quantitatively the digit-specific contributions as well as the phalangeal segment-specific contributions of the fingers to the total hand force in the power grip of tool handles of various sizes and shapes. This paper also presents examples of patterns of hand contact force distribution associated with other common grip and pinch configurations.

*Keywords: hand tools, hand ergonomics, grip force measurement*

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## 1. Background

Thin profile force/pressure sensors have been used previously in several studies to quantify hand and finger contact force in hand grips [e.g. 1,2,3]. Advances in the design of resistance-based force sensors have occurred since the early 1990's which may make the current technology better suited to applications involving hand grip force. Most notable is the linear response between applied force and voltage output of the sensors. This paper describes the development of a measurement system using thin profile conductive polymer resistance-based force sensors attached to a glove for the measurement of hand contact force. While the system has many potential applications, to date it has been used primarily for the purpose of ergonomic evaluation of

hand force exertion on hand tools.

High hand force exertion has been identified as a risk factor for work related musculoskeletal disorders (WMSDs) of the upper limbs, particularly when combined with awkward posture and repetitive motion.

Unlike posture and repetitive motion, which are associated with observable changes in the position and displacement of joints and limb segments, the magnitude of hand force exertion is more difficult to assess visually. Thus, it is believed that a system to reliably quantify hand force will greatly benefit efforts to assess risk for WMSDs.

## 2. System configuration

This system incorporates 20 conductive polymer resistance-based force sensors (Tekscan, Flexiforce® A101, 25 lb capacity) attached to a thin leather athletic grip glove over the regions shown in Figure 1. The active area of each sensor is circular with a diameter of 9.53 mm. The thickness of each sensor is 0.127 mm. The sensors have leads that are wrapped behind the glove where they terminate at a connector held in place with a Velcro strap on the dorsum of the wrist. The athletic grip gloves are available in incremental sizes so that a form-fitting glove can be acquired for almost all hand sizes.

Raw data are sampled via a pc and digitized through a 12-bit data acquisition board set to a  $\pm 5V$  range. The raw voltage data from the sensors are converted to calibrated force units and displayed in real time.



Fig. 1: Sensor placement on the force glove.

### 3. Sensor calibration

We have established a two step calibration procedure in which the gain of the signal amplification is adjusted individually for each sensor, and then the sensors are individually calibrated. The gain is scaled such that a 5 kg load results in approximately 2V deflection on a virtual oscilloscope. This represents approximately 40% of full scale for the data acquisition board (5V) and the sensor's rated force capacity (11.31 kg = 25 lb). Our testing has indicated that these sensors lose sensitivity over repeated loading/unloading cycles.

When setting the sensor gain, if a sensor can not achieve an output of 2V under a 5 kg load with the available gain of the amplifier the sensor is discarded and replaced.

After the gain is set for all sensors each sensor is individually calibrated. The sensor is placed between the investigator's thumb and a flat metal platform mounted over a button style load cell. The investigator manually applies a thumb force, ramping from zero force to approximately 7 kg and back to zero force, over an approximately 6 sec. interval. A least squares linear regression is fit to the force vs. sensor voltage output. A typical linear calibration response is shown in Figure 2. The high linearity of response typically results in an  $r^2 > 0.99$ .

The importance of this physiologically relevant calibration procedure, that involves establishing the force vs. voltage relationship under loading conditions that replicate the conditions under which the measurements are made, is evident in Figure 3. Figure 3 shows the degree of agreement between load measurements made under two calibration conditions (designated by "C") and two measurement conditions (designated as "M"). The physiologic calibration procedure (PC) involves the calibration loading procedure using the thumb tip, as described above. The mechanical calibration procedure (MC) uses a cylindrical rubber "puck" to distribute the applied load over the sensor area. All measurements were made by applying forces on the Flexiforce sensor attached over the finger regions of the Digits-Grip System (NK Biotechnical System), which is designed for finger specific measurements of contact force on a digital hand grip dynamometer. Physiological measurements (PM) were made with the finger applying the load to the Flexiforce sensor and mechanical measurements (MM) were made with an externally applied load transmitted through the rubber puck. Agreement between the Flexiforce-measured force and the NK system-measured force were clearly superior (nearer to a unity slope) when the calibration loading conditions ("P" or "M") matched the measurement loading conditions ("P" or "M"). Physiological calibrations of the Flexiforce sensors resulted in overpredictions of measured force as it was applied mechanically with the puck. More importantly for ergonomic applications, mechanical calibrations of the Flexiforce sensors using the puck resulted in measurements of physiological hand contact force that underpredicted the force level (Figure 3, bottom panel, open circles).

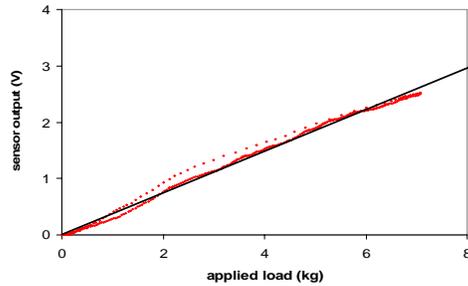


Fig. 2: Typical sensor calibration response.

#### 4. Studies to date

To date this force measurement system has been applied in studies of the grip of non-powered hand tools with cylindrical, or near cylindrical cross-sectionally symmetric handles. This type of handle is found in a variety of hand tools including, hammers, hand saws, and screwdrivers. Table 1 shows the average distribution of forces over the 16 finger segments for 24 subjects performing a maximum cylindrical power grip [4].

Predictable distributions of contact force on the hand are evident in preliminary assessments of grasp configurations other than the power grip. Placement of the sensors on the glove was chosen strategically so that patterns of contact force for the seven grasp types shown in Table 2 can be discriminated. Table 2 shows examples of these grips for two subjects estimating 50% of their maximum force output with these grip configurations. (Refer to Figure 4 for a spatial legend of the force distributions in Table 2.)

Preliminary work with this force glove system suggests that the magnitude of the grasp force may be influential on the ability to discriminate among grasp types based on the distribution of contact forces. At low levels of grip or pinch force sensors that are in contact with the object register low contact force. As these levels become very low it may be difficult to resolve principal points of contact from low voltage signal artifacts resulting from flexion and extension of the interphalangeal and metacarpal phalangeal joints., which bend the sensors. As such, the system may not be as effective in quantifying very low levels of contact force as it is in quantifying higher levels of hand force.

Since low levels of hand force are less of a concern as a risk factor for upper limb WMSDs this may not be a serious limitation of the system.

Table 1. Distribution of forces on the 16 finger segments in the maximum cylindrical power grip. Values are in units of Newtons (N) and percentage of total force.

	index	middle	ring	little
distal	45.9 (10.4%)	64.1 (14.5%)	48.8 (11.0%)	25.4 (5.7%)
middle	26.1 (5.9%)	36.5 (8.2%)	27.8 (6.3%)	14.5 (3.3%)
proximal	21.0 (4.7%)	29.3 (6.6%)	22.3 (5.0%)	11.6 (2.6%)
meta-head	17.3 (3.9%)	24.2 (5.5%)	18.4 (4.2%)	9.6 (2.2%)

#### 5. Discussion

Attaching thin profile pressure/force sensors to a glove has the advantage of facilitating measurements of hand force on any grasped object, such as a hand tool, without the need to instrument the tool itself. The disadvantage of this measurement approach is that the material properties of the glove and sensor may alter the frictional conditions between the hand and the tool and may degrade tactile representation of the coupling between the hand and the tool. If these limitations are acceptable the glove-based system is a useful measurement device for characterizing hand grip contact forces in the evaluation of many hand tools.

The glove system is also advantageous because of its low cost, and replaceable sensors. Through repeated use in industrial activities that involve high grip force levels we have observed damage and failure of the thin profile force sensors. These sensors are relatively inexpensive and can be replaced individually. Other commercial systems have been developed with multiple force sensing elements embedded within a single printed medium. If one of the sensing elements in this medium is damaged the entire sensor medium must be replaced – at significant cost.

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*Note: The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of any company names or products does not constitute endorsement by the National Institute for Occupational Safety and Health.*

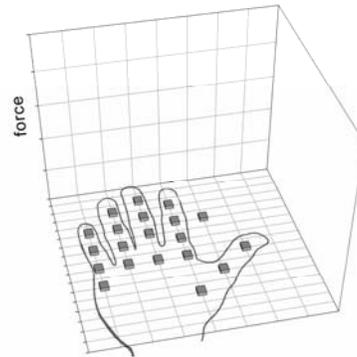


Fig. 4: Spatial legend for the bar graphs in Table 2. The sensor shown to the right of the index finger is attached on the lateral aspect of this finger.

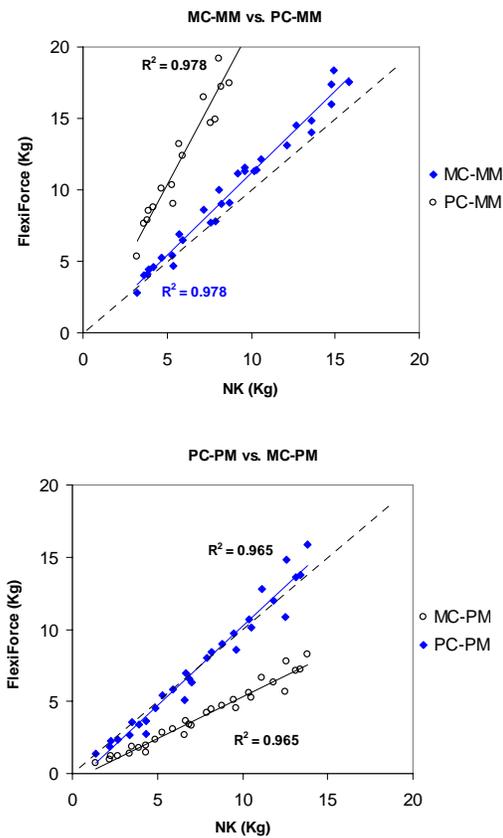


Fig. 3: Comparison of a physiological calibration with a mechanical calibration. (PC – physiologic calibration, PM – physiologic measurement, MC – mechanical calibration, MM – mechanical measurement).

Table 2. Example hand force distributions (two subjects) for seven common grasp types at approximately 50% MVC. Refer to Figure 4 for a spatial legend of forces on the hand.

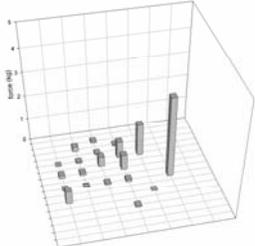
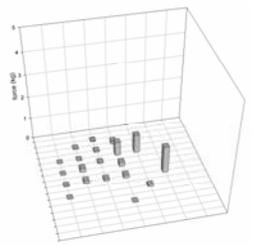
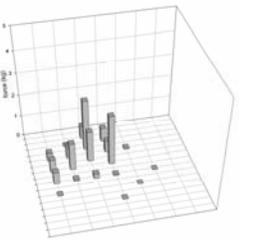
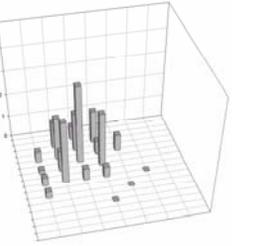
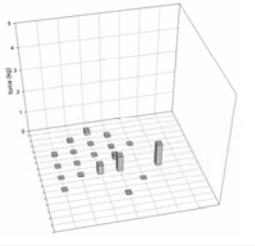
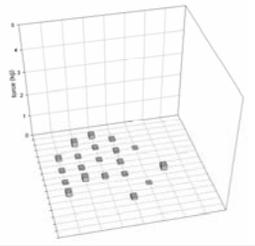
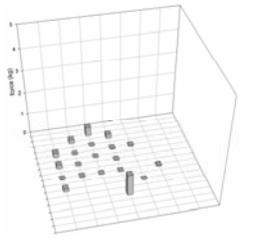
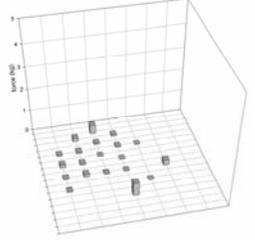
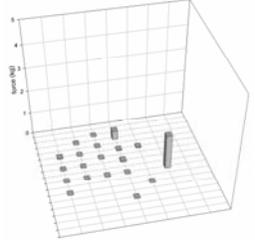
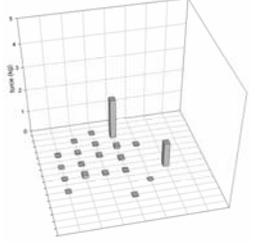
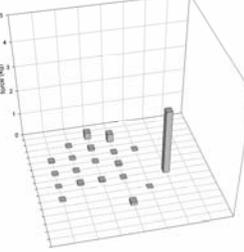
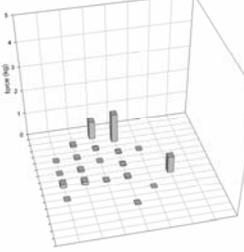
grasp type	photograph	hand force distribution (subject 1 on left, subject 2 on right)	
lateral pinch (key pinch) <i>ex. grasp of a key or                      “dog ear” paper clip</i>			
hook grip <i>ex. carrying a tray                      with cut out handles</i>			
palm pinch <i>ex. lifting/supporting                      glass</i>			
hand press (palm press) <i>ex. exerting a press                      force</i>			
pulp pinch (two point) <i>ex. precise grip and                      insertion of a part</i>			

Table 2. (continued)

<p>pulp pinch (three point, or chuck) <i>ex. turning a knob</i></p>			
<p>palm grasp <i>ex. opening a jar</i></p>		