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Relationship among Hand Forces Imparted on a Viscoelastic Hand-Handle Interface

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Abstract

Design of a flexible thin-film hand sensor is presented for reliable measurements of the contact pressure/force distribution at a viscoelastic hand-handle interface, including the contact force developed by a gloved-hand grasping a tool handle. The static properties of the developed hand sensor were evaluated in terms of its drift, linearity, repeatability and hysteresis under global as well as local loads. The measured results revealed low hysteresis (<6%) and drift (≈2.9% over 30s), good linearity (r^2=0.99) and repeatability (CoV=1.5%). Subsequently, an experiment was designed to establish a relationship among the grip, push and contact forces imparted on a flexible hand-handle interface. The hand-handle contact force was measured considering three interface conditions: (i) bare hand grasping an instrumented rigid handle (BH); (ii) hand grasping the instrumented handle covered by an anti-vibration material (MT); and (iii) gloved hand grasping the handle (GV). The measurements with each interface were conducting with five male subjects and nine combinations of grip (10, 30 and 50 N) and push (25, 50 and 75 N) forces. The measured data were analyzed via multiple linear regression method to explore relationships among the grip (F_g), push (F_p) and contact (F_c) forces for each hand-handle interface. The data were further analyzed to investigate the effect of anti-vibration (AV) gloves on the hand grip strength. The relationship obtained for the hand grasping a rigid handle showed good agreement with those in the reported studies, which verified the hand sensor feasibility for application to curved surfaces. The relationship obtained for the bare hand grasping the handle with flexible anti-vibration material, however, showed higher coefficients of grip (α_g) and push (α_p) forces compared to those observed with the rigid handle of the same diameter. A similar trend was also obtained for the gloved hand grasping the handle, which suggested higher grip strength demand

for a gloved hand (GV) and hand coupling a viscoelastic handle (MT) compared to the BH condition for realizing the same level of grip/push force combination.

***Keywords**:* Hand force sensor, anti-vibration gloves; hand-handle contact force; hand forces; sensor calibration.

1. Introduction

Prolonged exposure to hand-transmitted vibration (HTV) arising from hand-power tool interactions has been associated with an array of disorders in the vascular, sensorineural, and musculoskeletal structures of the human hand-arm system, collectively referred to as the hand-arm vibration syndrome (HAVS) (Thompson & House, 2006). The risk of HAVS among hand-held power tools operators is related to mechanical coupling of the hand with a tool handle apart from the nature of HTV exposure. The HTV exposure is generally assessed using frequency-weighted acceleration of the vibrating tool handle and the dose-response relationship defined in ISO 5349-1 (2001), while the effect of hand-handle coupling force is not considered. It has been reported that the magnitude of the coupling force imparted on a vibrating tool handle affects the severity of the HTV exposure and hand-wrist cumulative trauma disorders (Adewusi, Rakheja, Marcotte, & Boutin, 2010; Aldien, Marcotte, Rakheja, & Boileau, 2005; CEN/TR 16391:2012). Hand-handle coupling force has been defined as the sum of the hand grip and push forces imparted on a tool handle (ISO 15230, 2007). There is evidence that reducing the coupling force is likely to decrease the injurious effect of exposure to HTV. Moreover, greater grip and push forces yield increased electrical activities of the flexor carpi ulnaris and finger-flexor muscles, which may adversely affect peripheral circulation of the fingers (Gurram, Rakheja, & Gouw, 1995; Huesler, Maier, & Hepp-Reymond, 2000; Vigouroux, et al., 2007; Yu et al. 2015).

Considering the important effects of hand-handle coupling force, the CEN/TR 16391 (2012) has defined an additional weighting to account for the effect of hand-handle coupling force on vibration exposure risk. The significance of coupling force on the handle vibration has also been emphasized in ISO 5349-2 (2001), which recommends measurements of HTV under different levels of coupling force applied to the tool handle. A definite relationship between the coupling force and the HTV exposure, however, does not yet exist. The development of methods for reliable measurements of hand-handle coupling forces is thus vital to seek such a relation to assess the effect of hand forces on vibration exposure. Moreover, a few studies have established that AV gloves, widely used for attenuation of HTV, significantly alter the hand-handle contact force and impose greater demand on the hand forces and thus higher risk of hand-arm musculoskeletal disorders (MSDs) such as hand tendonitis, strained muscles, and carpal tunnel syndrome (Chang & Shih, 2007; Wimer et al., 2010; Beschorner et al., 2017). These have employed indirect measurements of grip strength via instrumented handles and hand force dynamometers (Horsley, et al., 2016; Willms, Wells, & Carnahan, 2009). This further suggests the need for the development of an effective measurement system for quantifying the hand-handle contact forces developed at the flexible gloved hand-handle interface.

Although the significance of coupling force and grip strength on the hand-arm vibration dosage and potential injury risk has been widely recognized, the measurements of coupling force on power tools have met only limited success (Kalra, et al., 2015; Marcotte, et al., 2005; Welcome, et al., 2001; Lemerle et al. 2008). This is due to the lack of reliable methods for measurements of forces developed at the tool handle-hand interface, especially for field applications. The measurements of grip and push forces, and thus the coupling force, imposed on handles have been conducted via instrumented cylindrical and elliptical split handles in conjunction with a force plate in a laboratory setting (Seo & Armstrong, 2008; Welcome, et al., 2004). Cylindrical instrumented handles or dynamometers have also been applied for measurements of grip forces on bicycle handles (Odenwald & Krumm, 2014) and grip strength (Savva, Karagiannis, & Rushton, 2013; Young, Woolley, Armstrong, & Ashton-Miller, 2009) to study the effects of handle size and shape (Irwin, Towles, & Radwin, 2015; Seo, Armstrong, Ashton-Miller, & Chaffin, 2007; Young, Woolley, Ashton-Miller, & Armstrong, 2012). The cylindrical or elliptical cross-sections, however, do not represent the geometries of many tool handles. The grip force measured with such handles may not accurately describe that applied to a real tool handle (Wimer et al., 2010). Moreover, applications of an instrumented handle and force plate for measurement of coupling force on a tool implies not only high cost and design complexities, but also possible ergonomic impairments.

ISO 15230 (2007) provides definitions of hand-handle coupling and contact forces and guidance for measurements of these forces and related parameters using a flexible pressure-sensing mat. A few studies have explored the feasibility of thin-film and flexible pressure sensing systems that can be applied to handles with varying cross-section and curvature for measurements of contact pressure, and contact and coupling forces. Fukubayashi and Kurosawa (1980) used the Fuji Film Prescale Pressure Measuring System to measure contact area and contact pressure distribution in the knee. This method is widely being used in orthopedics and bioengineering research, although the method cannot provide real-time measurements due to complex signal processing and analyses. Semiconducting, capacitive and resistive thin film sensors, comprising pressure-sensitive capacitors and resistors, respectively, have been successfully used to measure hand-handle contact forces under static conditions (Aldien, 2005; Bachus, et al., 2006;Misiewicz, et al, 2015; Wirz, et al, 2002; Young, Sackllah, & Armstrong, 2010; Scalise & Paone, 2015). Bachus et al. (2006) compared the performance of measurement systems employing pressure-sensitive Fuji film and resistive sensors, and concluded that the resistive sensing grid yields more accurate measurements of contact area and pressure than the Fuji film. The capacitive pressure sensing grids, developed by Novel GmbH (Germany), have been applied to cylindrical and elliptical handles to quantify hand-grip pressure distributions and relationships among the grip, push and contact forces as a function of the handle size (Aldien, 2005; Welcome et al., 2004). Lemerle et al. (2008) used a hand sensor comprising capacitive pressure sensors to measure the grip and push forces on power tools' handles. Zheng et al. (2016) used thin-film resistive bend and force sensors for assessing functions of a gloved hand in terms of finger joint angles and force exerted by fingers. The study employed a glove made of stretchable cloth.

Aforementioned studies have clearly demonstrated the feasibility of capacitive pressure-sensors for reliable measurements of hand-handle interface pressure distributions and coupling forces. The measurement system, however, is not considered to be well-suited for field applications due to its very high cost. Moreover, the capacitive sensors are known to be relatively fragile and may incur damage and/or failure during field applications. Alternatively, a few studies have explored low-cost force sensing resistors (FSR) for hand-handle interface force measurements. Seo et al. (2008) used a resistive pressure-sensing matrix, developed by Tekscan Inc. (USA), to establish a relationship among the grip and normal forces, and contact area for cylindrical handles and its dependence on the handle and hand sizes. The I-scan software, developed by Tekscan, permits equilibration of sensels within a sensing matrix via appropriate correction factors that are identified by subjecting the sensors to uniform pressure (Tekscan, 2012). It has been reported that equilibration of the resistive sensing systems could effectively reduce the individual variance of the pressure-sensing elements (Misiewicz et al., 2015). Rossi et al. (2012) applied resistive pressure sensors to study the influence of handle diameter on the hand forces. Kalra et al. (2015) applied two low-cost thin film resistive sensors on opposite sides of a tool handle in the grip direction to measure the coupling force at the hand-handle interface under static and dynamic conditions. While the individual sensors showed good linearity and repeatability of measurements, considerable drift and notable differences were reported among different sensors (Brimacombe et al., 2009; Ferguson-Pell, Hagisawa, & Bain, 2000; Misiewicz et al., 2015; Wilson, Apreleva, Eichler, & Harrold, 2003).

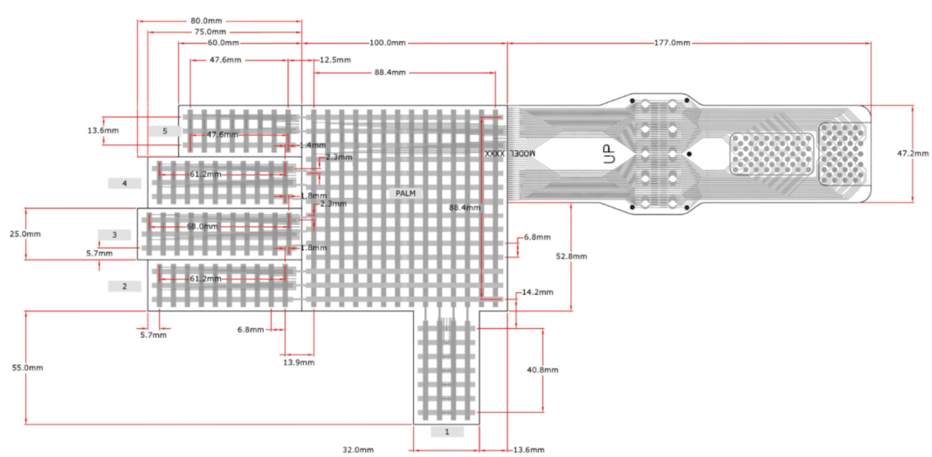
In the aforementioned studies, the hand-handle pressure measurement systems have been, invariably, applied for measurements of coupling force and contact force/pressure at the rigid handles. A tool handle enclosed by a vibration isolation material, however, constitutes a viscoelastic hand-handle interface, which may affect the distribution of contact pressure and thus the force. Moreover, through measurements of contact force imposed by a gloved hand on rigid handles, it has been shown that AV gloves affect operators' grip strength in an adverse manner, suggesting higher musculoskeletal loads with an AV glove (Hamouda, Rakheja, Dewangan, & Marcotte, 2018). This may be due to viscoelastic properties of the gloved hand-handle interface, while measurement of contact force at a viscoelastic interface has not yet been attempted. Effect of a viscoelastic AV glove on the grip strength can be evaluated through measurements at the interface of the hand and the glove. Moreover, it has been suggested that effectiveness of the vibration reducing materials used in AV gloves can be enhanced through reduction in the fingers' contact force (Xu et al., 2019). The quantification of forces imposed by the fingers and the palm will necessitate applications of the force/pressure-sensing grid inside the glove between the hand and the glove. Development of a hand sensor that can be applied to a viscoelastic interface or within the AV glove can not only help quantify the effect of the viscoelastic interface on the grip strength but also a relationship among the hand forces applied to tool handles with viscoelastic material coverings such as handle grips.

In this study, a hand-force measurement system for acquiring viscoelastic hand-handle interface force/pressure is developed and evaluated. The hand sensor, comprising thin flexible pressure-sensitive resistive sensels, could be applied for measuring the contact force distribution at the viscoelastic hand-handle interface and may be inserted into the AV glove to study the effect of AV gloves on the grip strength. The static properties of the hand sensor in terms of linearity, hysteresis and repeatability are evaluated under local as well as global loading of the sensor on a flat surface. The feasibility of the hand sensor applied to a curved surface is evaluated by applying it to an instrumented rigid handle capable of measuring hand grip and push forces. The contact forces developed at the rigid and viscoelastic hand-handle interface are measured under different combinations of the hand grip and push forces, and the data are analyzed to establish relationships among the grip/push and contact forces. The effectiveness of the hand sensor for measurements of the contact force between the hand and an AV glove is further evaluated.

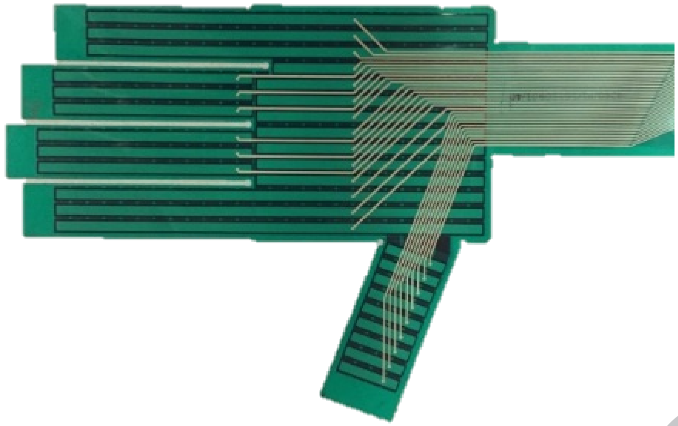
2. Hand Sensor Design and Assessments

The hand sensor was designed for measurement of contact force distribution at the flexible hand-handle and hand-glove interfaces. The sensing matrix was based on relatively low cost pressure-sensitive resistive sensels. The sensor was designed so that it could be mounted on the hand surface to capture the contact force distributed at each digit of the hand and of the palm region. The sensor could also permit measurement of the contact force of the gloved hand, when an AV glove is worn over the hand with the sensor. The dimensions of the palm and fingers regions were chosen to ensure its fitting to the hand size of 10 in accordance with the EN 420 standard (2010). The sensing matrix was designed with five sensitive strips for accommodating five digits of the hand, which were connected to a sensing grid in the palm region, as shown in Figure 1(a). The sensor was fabricated by Tekscan Inc. (Tekscan, South Boston, MA, USA), which also provided the data acquisition (DAQ) system together with the I-Scan software (Tekscan, 2012). The hand sensor is made of a matrix of pressure-sensing elements (denoted as ‘sensels’) sandwiched by two layers of thin-film sheets, as pictorially illustrated in Figure 1(b). The 0.1 mm thick flexible sensing matrix is printed on a polyester sheet both horizontally and vertically (Tekscan 2012). The intersections of these horizontal and vertical arrays created the sensels. Each sensel thus contains a pair of intertwined conductors enclosed by an adhesive layer coated with pressure-sensing ink, which formed the effective sensing area. The sensing area could measure the change in sensel resistance in response to an applied pressure, which was acquired and processed in the I-Scan software to determine the distributed contact force. The sensor was designed with a total of 372 sensels including 196 sensels in the palm sensing grid, 36 sensels within each of the thumb, and index and ring finger regions, and 39 and 30 sensels in the middle and little fingers regions, respectively. The effective area of each sensel is 0.46 cm^2, while the total effective sensing area of the sensor was 171.98 cm^2.

Apart from the above, the sensor design involved considerations of other factors. These included the sensor flexibility for its applicability to the curved rigid as well as viscoelastic handle surfaces with minimal interference with the hand/fingers movements, and low cost and sufficient robustness for applications in real tool handles. The software also computes the overall contact force, the force developed within the individual regions, mean and peak contact pressure within each region, and the center of pressure. Owing to wide variations in the hand-handle contact pressure (Aldien et al., 2005), good sensitivity of the sensing matrix to local as well as overall loading constituted another important design criterion. The studies reporting pressure distributions at the viscoelastic and rigid seats have shown that the peak contact pressure observed at a viscoelastic interface is substantially lower than that at the rigid interface (Wu, Rakheja, & Boileau, 1999). The I-Scan software permitted scalable gains to ensure nearly uniform sensitivity of the measurement system over different desired ranges. The maximum pressure measurement range of the hand sensor, 0 to 2.76 bar (40 psi), corresponded to the lowest sensitivity level. A higher sensitivity level could be chosen for a lower pressure range that was expected for a viscoelastic interface. Moreover, the sampling frequency of the I-Scan system could also be varied from as low as 0.015 Hz to a maximum of 730 Hz.



(a)



(b)

Fig.1: (a) Dimensions of the sensing grids in the fingers and palm regions; and (b) pictorial view of the hand-sensor.

2.1 Hand sensor calibration

The I-Scan software expresses the change in resistance of each sensel in terms of a digital output ranging from 0 to 255 (raw sum). The relationship between the raw sum and the applied force within a selected measurement range was established via calibrations using the two-point power law method, as recommended in (Tekscan 2012). The sensor calibration was performed by subjecting all the sensing elements to a uniform controlled pressure via an air bladder. The sensor was pre-conditioned prior to the calibration by repeatedly loading and unloading the sensor with a uniform peak pressure of about 2 bars (five times). Subsequently, a pressure sensitivity gain was selected for the desired measurement range to ensure good resolution of the measurement and to avoid sensels' saturation. Two different measurement ranges were considered for the rigid and viscoelastic hand-handle interface conditions. The mean peak contact pressure imposed by the bare hand grasping a 40 mm diameter rigid handle with 50 N grip and 75 N push forces has been reported to be in the order of 1.41 bars (Aldien et al., 2005). A measurement range of 0 to 2 bars was thus selected for measurements with the rigid handle. The measurement range for the viscoelastic hand-handle interface was estimated as 0 to 1 bar. The sensor calibrations were thus performed for these two measurement ranges using appropriate sensitivity gains.

The resistive sensors may exhibit variabilities due to non-uniformity of the pressure-sensitive ink. Misiewicz et al. (2015) reported that equilibration of the sensing system could effectively reduce the effect of variance among the individual pressure-sensing elements. Through equilibration, the I-Scan system computes and applies appropriate correction factors to compensate for such variations. The equilibration of the sensels was thus performed by applying uniform pressures of 0.5, 1 and 1.5 bars in a sequential manner. Subsequently, the hand sensor was calibrated via a two-point power law method. Two different pressures, 20% and 80% of the maximum load, were applied to the hand sensor via the air bladder. Each pressure loading was held for a duration of 30 s so as to achieve steady-state loading of the sensors by the air bladder. The relationship between the raw sum and the force was established in the form of $y=ax^b$ for the two measurement ranges considered.

The measurement accuracy of the hand sensor was subsequently evaluated under different uniform pressures (0, 0.5, 1, 1.5 and 2 bars). The applied force was computed for each pressure loading on the basis of the effective sensor area (171.98 cm^2). The distributed force signals were recorded as a movie for a duration of 30 s at the rate of 1,000 frames/s for each input pressure. The selected period was consistent with that used during the calibration. Table 1 compares the mean measured force obtained from the measured data during the 30 s interval with the computed force for each pressure loading. The table also presents the residual error between measured and applied force. The results show a peak residual error of 2.2%, which suggests that the sensor can measure the overall force accurately when applied uniformly on a flat surface. The error is likely caused by a slight drift in the measurement, which has also been reported in studies on similar sensors (Shaw et al., 2009; Komi et al., 2007) The time-dependency of the measurement was examined by monitoring the measured force signal under 1 bar uniform pressure (applied force=1720 N) for a duration of 60 s. When compared to the applied force, the measurements showed drift in the mean force of 1.7%, 2.9% and 4.6% for respectively the intervals of 15 s, 30 s, 60 s. These suggest that the sensor response exhibits a sufficiently long time constant for accurate measurements of the static and dynamic hand force.

Table 1: Comparison of the mean measured and applied force magnitudes

Applied pressure (bar)	Applied force (N)	Measured force (N)	Residual error
0.5	860	852.5	-0.9%
1.0	1720	1740.6	1.2%
1.5	2580	2636.2	2.2%
2.0	3440	3498.8	1.7%

2.2 Static characteristics of the hand sensor under global and local loading

The static characteristics of the hand sensor were evaluated in terms of linearity, repeatability and hysteresis of measurements under static loads applied to the entire sensor placed on a flat surface. The entire sensor area was subjected to loads of 14.8 N, 36.4 N, 85.4 N, and 140.3 N in a sequential manner through a flat aluminum plate via a loading indenter. An elastomer was also placed between the loading plate and the sensor to achieve a nearly uniform contact with the sensor (Figure 2). The 8 mm thick elastomer was cut in the shape of the sensor in order to apply uniform loading of the fingers and palm sensing grids.

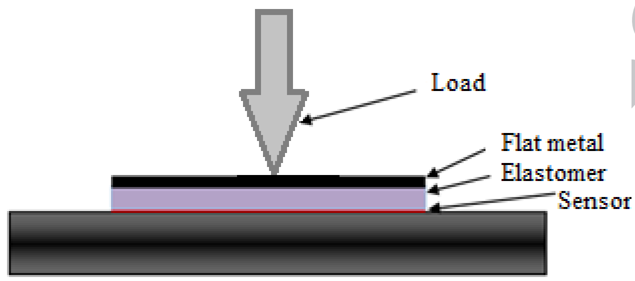


Figure 2. Loading of the hand sensor through an aluminum plate and elastomer.

Before applying the load, the hand sensor was zeroed to remove the force due to the elastomer and the aluminum plate. The sensor load was then gradually increased to 140.3 N and decreased to 0 N, and the sensor signal was recorded for an interval of 30 s under each discrete load. The measurements for each loading and unloading cycle were repeated three times. Figure 3 illustrates the variations in the measured force with the applied force. The linearity of the measurement was evaluated from the means of the loading and unloading curves obtained during the three loading/unloading cycles. The results revealed strong linearity of the hand sensor with r^2 values in excess of 0.99, while the peak hysteresis was below 6%. The coefficient of variation (CoV) of the mean was obtained as 1.5%, which suggested good repeatability of the measurement.

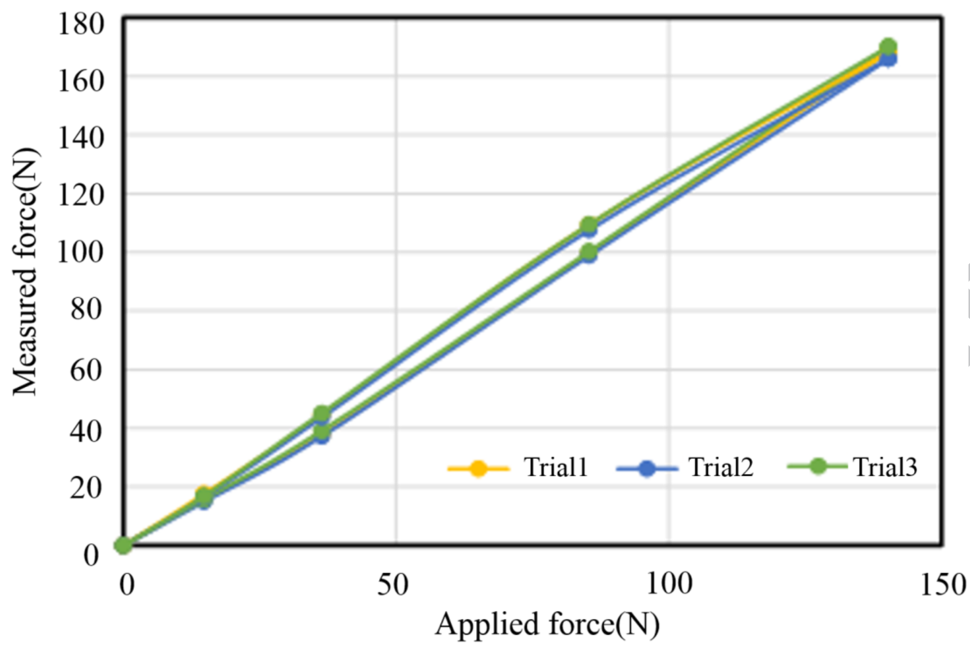


Figure 3. Variations in the measured force with the applied force during three loading and unloading cycles.

The effectiveness of the hand sensor in capturing a locally applied force was also evaluated under loads applied to selected local regions, which would be expected for the hand grasping a handle. The measurements were performed by subjecting the palm, thumb, and index and middle fingers sensing areas to a constant load in a sequential manner. A constant load of 21.56 N was applied to each finger region, while the palm sensing area was subject to a load of 49 N. The loading was applied by a flat aluminum plate and the elastomer, as in the case of global loading (Figure 2). The elastomer was sized appropriately to ensure the loading of the selected region alone. Each measurement was repeated three times. Table 2 summarizes the mean, standard deviation and measurement error for each locally loaded region. The results show measurement errors below 2% and peak CoV below 5%. It is thus deduced that the hand sensor is equally effective for accurate measurements of locally applied loads.

Table 2: Variability in the measurement under locally applied loads

Applied region	Applied force (N)	Measured force (N)			Mean	Standard deviation	Error (%)
		Trial1	Trial2	Trial3			
Thumb	21.56	22.69	20.75	21.90	21.78	0.80	1.03%
Index finger		20.98	21.08	21.35	21.14	0.16	-1.96%
Middle finger		21.89	20.54	21.22	21.21	0.55	-1.6%

Part of palm	49	49.6	47.6	48.5	48.6	0.8	-0.9%

3. Measurements of the hand-handle contact force - Methods

An experiment was designed to evaluate the effectiveness of the hand sensor to measure hand-handle contact force considering three different interface conditions. These included: (i) the bare hand grasping a rigid handle (RH); (ii) bare hand grasping the handle enveloped by a viscoelastic material (FH); and (iii) a gloved hand grasping the handle (GV). The primary motivation for the experiment derives from the need to define relationships between the grip and push forces, and the contact force for the rigid and viscoelastic hand-handle interfaces. Moreover, the direct measurement of contact force developed by the gloved hand will facilitate the assessment of the effect of AV gloves or viscoelastic handle coverings on the grip strength, which has been widely reported on the basis of indirect measurements (Marcotte et al., 2005; Welcome et al., 2004). The experiment for each interface condition involved nine combinations of grip (10, 30, and 50 N) and push (25, 50, and 75 N) forces. Five healthy right-handed male subjects were recruited for the study with a hand size of 9 in accordance with the EN 420 standard (2010). None of the participants had prior experiences in working with hand tools. The aim of the study and experimental procedures were described to each participant together with his rights and responsibilities. Each participant consented to the experimental protocol, which had been approved by the Human Research Ethics Committee of Concordia University.

The calibrated hand sensor was attached to the palm and fingers of the right hand of the participant using medical tape, as shown pictorially in Figure 4(a). The contact force was initially measured for the rigid hand-handle interface to evaluate the effectiveness of the hand sensor, considering the reported hand forces relationships in (Marcotte et al., 2005; Welcome et al., 2004). This also provided feasibility of the sensor's application to a curved handle surface. Experiments were performed with a 40 mm diameter and 140 mm long split cylindrical handle, which integrates two single-axis force sensors (Kistler 9212) for measurement of the grip force (Figure 5). The instrumented handle was installed, using a mounting bracket, on an electro-dynamic shaker in a horizontal plane to permit gripping of the handle along the Z_h-axis. Another two force sensors (Kistler 9317b) were placed between the handle and the exciter for the measurement of the push force imparted by the hand on the handle (Figure 5). Each subject was advised to grasp the handle with the required combination of the hand grip and push forces, while standing upright assuming the posture described in ISO 10819 (2013) as shown in Figure 4(b). The forearm was held nearly horizontal with an elbow angle of 90 ± 15 degrees, and neutral wrist position, while the elbow was not permitted to touch the body. The applied grip and push forces, sampled at a rate of 4 Hz, were displayed on a computer screen mounted at the eye level of the subject, which permitted the subject to maintain hand grip and push forces near the desired combination. It should be noted that the shaker was merely used to provide support for the test handle since the hand forces were measured under static condition alone. Prior to the experiment, each participant was asked to perform a few practice runs by randomly applying three different grip/push force combinations among the nine combinations of grip (10, 30, and 50 N) and push (25, 50, and 75 N) forces using feedback from the displayed forces.

Figure 4: Pictorial views of the measurement setup: a) hand sensor fixed to the hand; b) subject's posture while grasping the handle; c) handle covered with a gel material; d) gloved hand with the hand sensor.

A total of 27 randomized trials, including three repeats, were performed for each subject. Prior to the measurements, the participant was advised to hold the hand with the sensor around the handle in a power grip position without making any contact with the handle. The hand sensor was zeroed to remove the residual pressure, if any. The subject was advised to grasp the handle with a desired grip/push forces combination and maintain it within a margin of ± 2 N for a period of 30 s. The hand-handle interface contact force signal for each force combination was acquired in the I-Scan data conditioning and acquisition system. Apart from the contact force, the time-histories of the grip and push forces, obtained from the instrumented handle, were also recorded for the duration of 30 s for each trial. Three trials for each grip and push forces combination were performed to verify the repeatability of the measurements. The participant was asked to relax for 1~2 minutes between the consecutive trials to avoid fatigue.

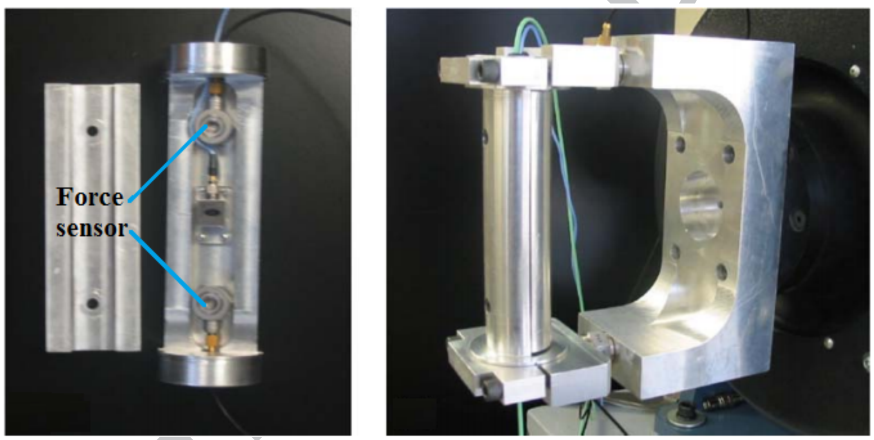


Figure 5: Instrumented cylindrical handle with grip and push force sensors (Marcotte et al. 2005)

Subsequently, the measurements were repeated for measurements of the contact force developed at the flexible hand-handle interface. For this purpose, a viscoelastic gel material used in AV gloves was wrapped around the handle, as shown in Figure 4(c). The contact force developed at the interface was measured for different combinations of grip and push forces. The order of the forces combination together with the three trials was randomized, as in the case of the rigid interface.

The final series of measurements were performed with the gloved hand grasping the rigid handle with the same combinations of the hand grip and push forces imparted on the handle. An AV glove, made of the same gel material used as the viscoelastic hand-handle interface, was used for the measurements of contact force via the hand sensor. This particular glove is considered as an AV glove as per the screening criterion defined in ISO 10819 (2013) The glove revealed vibration transmissibility magnitudes of 0.82 and 0.50 for the medium (25-200 Hz) and high (200-1250 Hz) frequency ranges in accordance with the standard (ISO 10819: 2013). The participant wore the selected glove over the hand with the hand sensor. A relatively large size (XL) AV glove was chosen so as to facilitate sliding of the glove over the hand with the sensor and to minimize damage to the sensor. Figure 4(d) illustrates the hand sensor inserted within the gloved hand. Subsequently, each subject participated in the measurements of the contact force developed by the gloved hand for three trials of the same combinations of grip and push forces in a random order.

3.1 Data analysis

The total contact force developed at a hand-handle interface was computed from the integration of the local pressure over the effective contact area within the I-Scan software. The effective contact area is defined as the area covered by active sensels of the sensor. A sensel is considered active, when its mean pressure exceeds the threshold value. The measurement system provided force threshold values of 0.018 N and 0.035 N, respectively, for the 1 and 2 bars pressure ranges, which were considered to provide a good compromise between the measurement accuracy and the signal noise. The total contact area is obtained by summing the areas of the active sensels, such that:

$$A_c = \sum_{i=1}^{n} \Delta A \tag{1}$$

where A_c is the total effective hand-handle contact area, $\Delta A = 0.46 cm^2$ is the individual sensel area and n is the number of active sensels. Since the sensel area is constant, the contact force F_c is computed assuming uniform pressure over the small sensel area, such that:

$$F_c = \Delta A \sum_{i=1}^{n} p_i \tag{2}$$

Where p_i is pressure measured by the sensel *i*.

The acquired data were analyzed to derive the mean contact force corresponding to each grip and push force combination. The standard deviation of the mean was used to evaluate the intra-subject variability of the measurements during the three trials. A relationship of the mean measured contact force with the corresponding grip and push forces was identified using multiple linear regression analysis. A relationship of the following form, as reported in (Marcotte et al., 2005), was attempted for each of the interface condition:

$$F_c = \alpha_0 + \alpha_g F_g + \alpha_p F_p \quad (3)$$

where coefficient α_0 represents the contact force offset of the hand sensor, and α_g and α_p are the coefficients representing the contributions due to the grip force F_g and push force F_p, respectively.

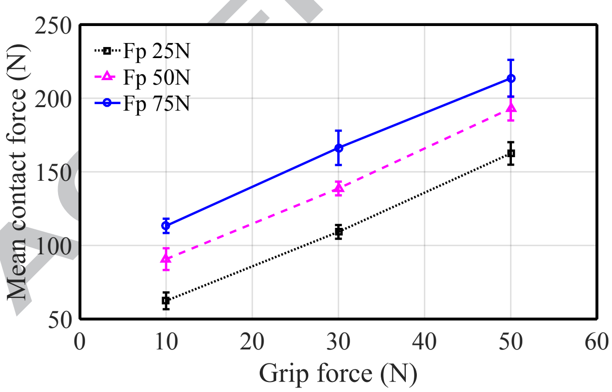
It has been reported that the grip and push force coefficients, α_g and α_p, depend upon the handle diameter. The effective diameter of the handle used for measurements of contact force at the elastic interface formed by the viscoelastic material or the AV glove was considerably higher than that the nominal diameter (40 mm) of the rigid handle. The mean diameter of the handle with 5 mm thick gel material was measured as 50 mm. For the purpose of relative analyses of contact force developed at rigid and viscoelastic interfaces, the contact force obtained for the 40 mm rigid hand-handle interface was adjusted to estimate the contact force for the 50 mm handle using the diameter dependence of the force relationship defined in (Marcotte et al., 2005; Aldien, 2005),

4. Results and discussion

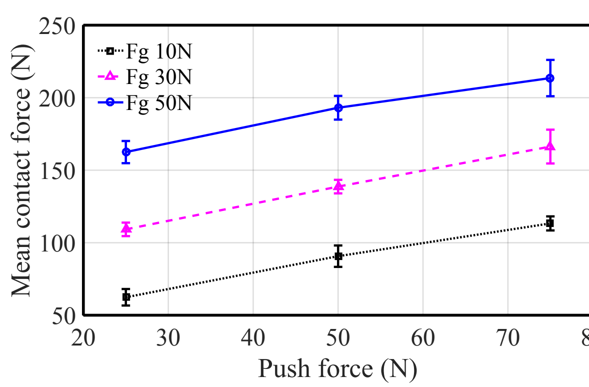
4.1 Contact force developed at the rigid hand-handle interface

The mean and standard deviations of the contact force measured during the three trials with different hand forces combinations revealed notable intra-subject variability in the measurements. The coefficients of variation (CoV) of the measurements ranged from 2.1% to 8.9% for the five subjects and the different hand forces combinations. Highest intra-subject variation was evident for combinations involving the highest push force (F_p=75 N), followed by those with the highest grip force (F_g=50 N). The grip and push forces data acquired for the combinations involving the highest grip and push forces also showed notable variations in the applied forces. The high intra-subject variability was thus attributed to the subjects' inability to maintain steady hand forces under the high grip and push forces.

Figures 6(a) and 6(b) illustrate variations in the mean contact force obtained for the 5 participants as functions of the applied grip and push forces, respectively. The figures also show standard deviations of the means corresponding to each grip/push force combination as error bars. The coefficients of variation (CoV) of the measured contact force ranged from 3.4% to 9%, which are similar to the intra-subject variations. Similar to the intra-subject variability, the data revealed higher inter-subject variations for combinations involving the highest grip or push forces (F_g=50 N or F_p=75 N), which is also evident from the error bars in Figs. 6(a) and 6(b). Welcome et al. (2004) and Aldien et al. (2005) reported inter-subject variability of the contact force measurements across 10 subjects in the order of 7-18% range for the 40 mm and 48 mm diameter handles. Relatively higher variability (10-20%) was observed in the data acquired for the 30 mm diameter handle. The contact force in both the studies was measured via a capacitive pressure sensing mat. The results in Figure 6(a) suggest nearly linear dependence of the mean contact force on both the applied grip force, irrespective of the push force magnitude. The variations in the push force cause a nearly constant shift in the mean contact force. The magnitude of this shift is similar to the change in the push force for each given grip force, which suggests a nearly direct contribution of the push force to the hand-handle contact force (α_p≈1). The mean contact force also varies nearly linearly with the push force for the given grip force, as seen in Figure 6(b). The change in the grip force in this case also causes a shift in the mean contact force. The rate of change of the mean contact force with the grip force, however, is substantially higher than that with the push force, which suggests a relatively higher contribution of the grip force to the hand-handle contact force.



(a)



(b)

Figure 6: Variations in the mean contact force measured on the 40 mm rigid hand-handle interface with: (a) hand grip force; and (b) hand push force.

A multiple linear regression analysis was performed using equation (3), in order to identify the grip and push force coefficients for the RH contact condition. The offset in the contact force (α_0) was set to 0 since the hand sensor signal was zeroed prior to each measurement. Correlation coefficients (r^2) for all the linear fits across the 5 subjects were greater than 0.94. Consequently, higher order fits were deemed unnecessary. The results showed close to unity mean push force coefficient (α_p) for the five subjects with mean and standard deviation (SD) of 1.15 and 0.09, respectively (Table 3). Conversely, the grip force coefficient (α_g) varied from 2.60 to 2.92 across the subjects with a mean and standard deviation of 2.75 and 0.12, respectively (Table 3). The observed grip and push force coefficients are comparable with those reported in (Marcotte et al., 2005; Welcome et al., 2004). Marcotte et al. (2005) reported that grip and push force coefficients of the contact force range from 2.71 to 3.13 and from 0.83 to 1.17, respectively, for the 10 subjects grasping a 40 mm diameter cylindrical handle. The mean ± standard deviations of α_g and α_p were 2.82±0.27 and 1±0.13, respectively. Similarly, Welcome et al. (2014) reported the mean grip and push forces coefficients of 2.87 and 1.10 for the nominal 40 mm diameter handle. Both the studies considered identical grip and push force combinations. It is thus deduced that the hand sensor design realized in this study can accurately measure the hand-handle interface contact force.

Table 3: Grip and push force coefficients obtained from multiple linear regression analysis of the data for five subjects and different hand-handle interface conditions.

Hand-handle interface	**Handle size**	**Coefficient**	**Subject**					**Mean**	**SD**	**CoV**
			A	**B**	**C**	**D**	**E**			
RH	40 mm	α_g	2.74	2.63	2.60	2.92	2.86	**2.75**	0.12	4.4%
		α_p	1.17	1.10	1.27	1.21	1.02	**1.15**	0.09	7.8%
		r^2	0.98	0.98	0.97	0.94	0.95	-	-	
RH	50 mm	α_g	$\alpha(D) =$ -0.0496D+4.878 (Aldien 2005)					**2.40**	0.26	10.8%
		α_p	$\beta(D) =$ 0.0022D+1.021 (Aldien 2005)					**1.13**	0.27	23.9%
		r^2	0.99					-	-	
FH	50 mm	α_g	3.46	2.66	3.04	3.16	2.96	**3.06**	0.26	8.5%
		α_p	1.88	1.29	1.30	1.41	1.11	**1.40**	0.27	19.3%
		r^2	0.91	0.93	0.97	0.90	0.92	-	-	
GV	-	α_g	3.71	3.08	3.41	3.62	2.74	**3.31**	0.36	10.9%
		α_p	1.74	1.67	1.61	1.29	1.29	**1.52**	0.19	12.5%
		r^2	0.91	0.83	0.93	0.89	0.96	-	-	

RH- Bare hand with a rigid handle; FH- Bare hand with resilient material; GV- Gloved hand

The results suggest that the contact force developed by the bare hand grasping a rigid handle constitutes about 2.75 times the grip force. In contrast, the push force contributes almost directly to the contact force. This is due to the fact that the push force is applied over a relatively small portion of the hand surface area (upper lateral side of the palm) normal to the handle axis. The grip force, on the other hand, is developed through compensation of the axial force components applied by the palm and fingers of the hand along the Z_h-axis alone (ISO 15230: 2007). The contact area of the palm and fingers is thus substantially higher compared to that encountered for the push force. Moreover, the grip force, as defined in (ISO 15230: 2007), neglects the contribution due to non-axial hand pressure on the handle surface. The relatively higher value of α_g compared to α_p accounts for the effect of the non-axial hand contact pressure on the resulting contact force.

4.2 Contact force developed at the viscoelastic hand-handle interface

The contact force data acquired with subjects grasping the handle covered with the viscoelastic AV material were analyzed to obtain a relationship among the hand forces, as described in Eq. (3). The data acquired during three trials for different subjects and grip/push force combinations revealed intra-subject variability in the 2.4% to 9.6% range. These are only slightly higher than those observed with the rigid handle. Highest variability was observed for combinations involving highest push (75 N) or grip (50 N) force, as in the case of the rigid hand-handle interface. The mean contact force obtained for the 5 subjects varied nearly linearly with the hand grip and push forces, as shown in Figs. 7(a) and 7(b), respectively. The figures also show standard deviations of the means corresponding to each grip/push force combination as error bars. The CoVs of the measured contact force ranged from 3.1% to 10.5%, which are also slightly higher than those observed for the rigid hand-handle interface (RH). The grip and push coefficients identified from the multiple regression analysis of the data acquired with each subject are summarized in Table 3 together with the means and standard deviations of the mean coefficients. The linear fits obtained for the 5 subjects revealed correlation coefficients (r^2) in excess of 0.9. Despite some variations between individuals, the mean grip and push force coefficients were obtained as 3.06 and 1.40, respectively, which are notably higher than those observed from the RH condition.

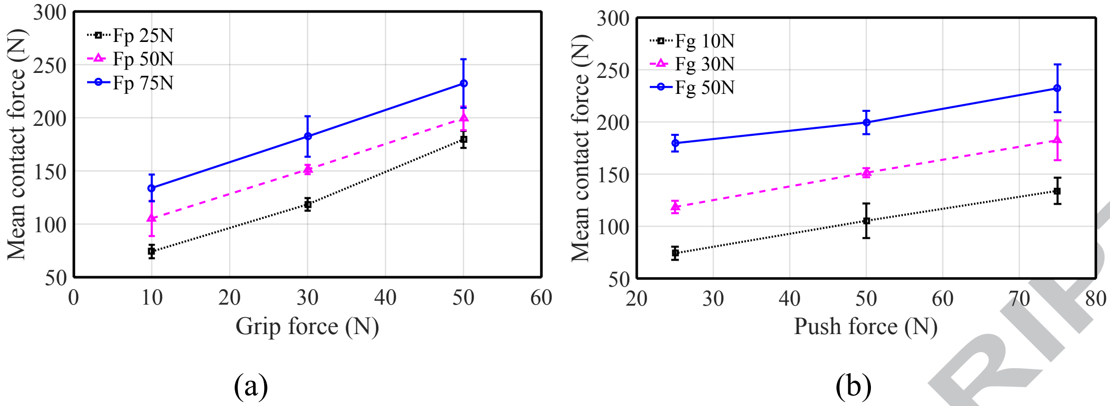


Figure 7: Variations in the mean contact force measured on the elastic hand-handle interface (FH) with: (a) hand grip force; and (b) hand push force.

The results obtained for the FH condition cannot be compared with those for the RH condition, since these two conditions represent the difference in the effective handle diameter. The effective handle diameter in the FH condition was 50 mm, while that of the handle in the RH condition was 40 mm. It has been reported that a larger handle yields higher effective contact area but lower mean contact pressure. The contact force tends to decrease with an increase in the handle diameter (Marcotte et al., 2005). The reported handle diameter dependency of the contact force (Marcotte et al., 2005) was used to obtain estimates of α_g and α_p for contact with a 50 mm rigid handle, in order to better compare the contact force with those obtained for the FH and GV conditions. The results presented in Table 3 suggest a relatively lower value of α_g (2.4) for the 50 mm handle compared to that for the 40 mm rigid handle (2.75). The value of α_p (1.13), however, is comparable with that of the 40 mm handle (1.15).

More pronounced differences between the RH and FH conditions are evident when α_g and α_p values are compared for the identical handle size of 50 mm. The results show a notably higher contribution of grip force to the contact force developed at the flexible interface compared to the RH condition. The grip coefficient (α_g) is about 27.5% higher for the FH condition compared to the RH condition considering the same handle size. The push force coefficient (α_p) also increased from 1.13 for the RH condition to 1.40 for the FH condition. The results suggest that grasping a viscoelastic handle interface would require higher contact force in order to achieve target grip and push forces, when compared to a rigid handle. The above suggests that for given grip and push forces grasping a handle with the viscoelastic AV material used in the study will impose nearly 28% greater grip strength demand from the subject, compared to the rigid handle. A recent study on the grip strength performance of different AV gloves has reported a 27% to 41% reduction in the grip strength compared to the bare hand (Hamouda et al., 2018). The study, however, measured the maximum grip strength of the participants with bare and gloved hands. The grip strength reduction due to a viscoelastic material covering is thus expected to vary with the viscoelastic properties of the material.

The effect of a viscoelastic interface on the contact force may also be attributed to the relatively higher effective contact area compared to the RH condition. Figure 8 compared the mean contact area obtained for the RH and FH conditions for the nine hand force combinations considered in the study. The FH condition leads to a substantially higher contact area, irrespective of the hand force combination. The mean contact pressure developed at a flexible interface was also higher, which leads to relatively higher contact force compared to the RH condition.

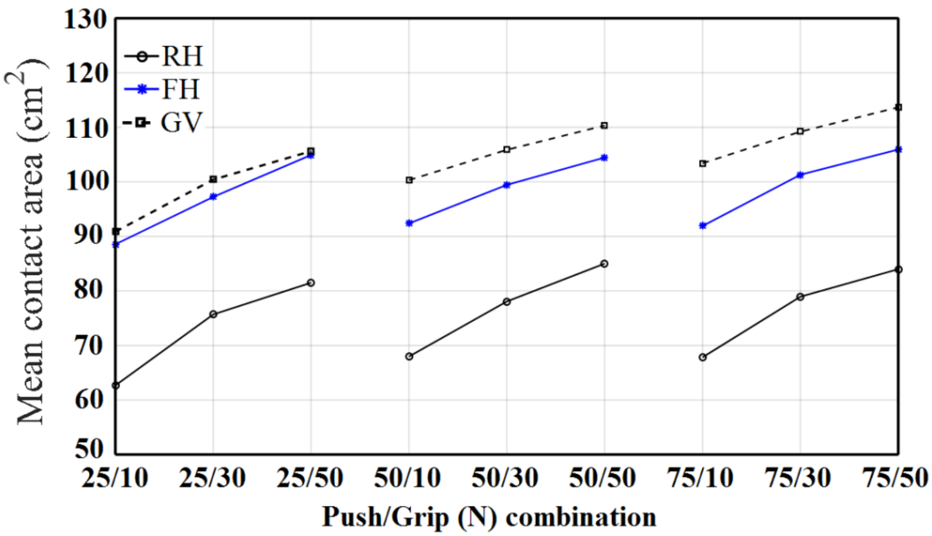


Figure 8. Comparisons of mean contact area attained for the rigid (RH), viscoelastic (FH) and gloved (GV) hand-handle interface conditions as a function of hand push and grip forces combinations.

4.3 Contact force developed by the gloved hand

The contact force acquired for the gloved hand grasping the handle revealed intra-subject variations in the 2.6 to 8.7% range, which is comparable with those observed for the RH and FH conditions. The measurements with the gloved hand, however, revealed considerably high inter-subject variations (7.9 to 17.4%) compared to the other conditions. This is likely caused by variation in the contact between the hand sensor and the glove across the subjects. The coefficients of grip and push forces derived from multiple linear regression equation are presented in the Table3. The coefficients of correlation ranged from 0.83 to 0.96 for the five participants. The mean values of α_g (3.31) and α_p (1.52) are higher than those obtained with the RH condition of comparable handle diameter (50 mm). The identified coefficients, however, are closer to those obtained for the FH condition. This is likely due to the fact that the GV and FH conditions employed identical viscoelastic material. The grip and push force coefficients identified for the five participants, however, showed considerably higher variations compared to the RH condition. The CoVs of α_g and α_p were about 10.9% and 12.5%, respectively, which are higher than those obtained for the FH condition.

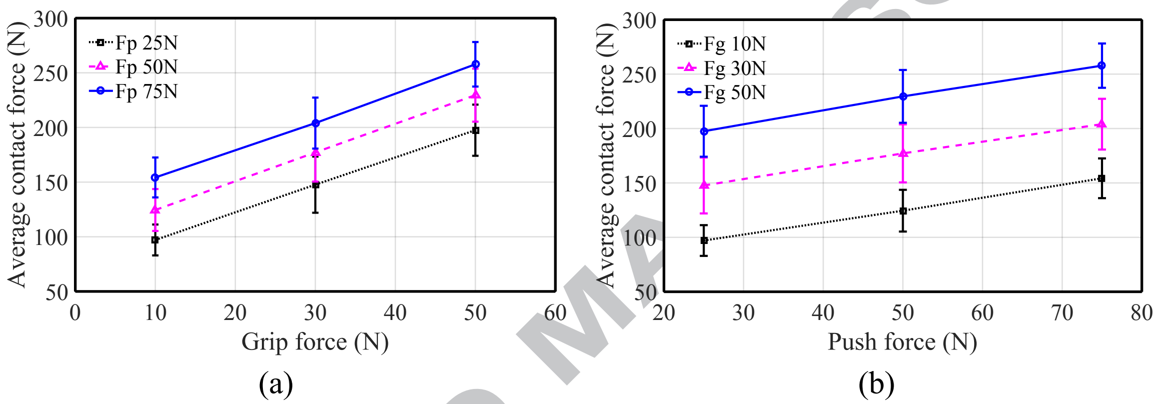


Figure 9: Variations in the mean contact force measured at the glove-hand interface (GV) with: (a) hand grip force; and (b) hand push force.

There are significant differences in the hand force coefficients (α_g and α_p) between the RH and GV conditions, although coefficient values are comparable for the FH and GV conditions. The grip coefficient α_g is about 37.9% higher for the GV condition compared to the RH condition. The push force coefficient α_p is also increased by 34.5%, from 1.13 for the RH condition to 1.52 for the GV condition. However, the grip and push forces coefficients for the GV condition increased by 8.2% and 8.6%, respectively, only, when compared with the FH condition. The results further suggest that grasping the handle with the AV glove requires higher contact force to achieve a target grip and push forces, when compared to the rigid handle. The use of AV gloves would thus involve relatively higher grip strength demand from the operator compared to the bare hand considering identical hand grip and push forces. The effective contact area of the gloved hand is also considerably higher compared to the RH condition but only slightly higher when compared to the FH condition, as shown in Figure 8. The difference in the mean contact area is notably higher for higher push forces (50 and 75 N).

The correlation of the contact force with the coupling force, defined as the sum of the applied grip and push forces (ISO 15230, 2007), is also illustrated in Figure 10 for the three interface conditions and nine hand force combinations considered. The results show a linear dependence of contact force on the coupling force, irrespective of the handle interface conditions. The results suggest that the viscoelastic interface due to AV material or AV glove leads to higher contact force compared to the RH condition for the entire range of coupling force considered. This is also evident from grip and push coefficients presented in Table 3.

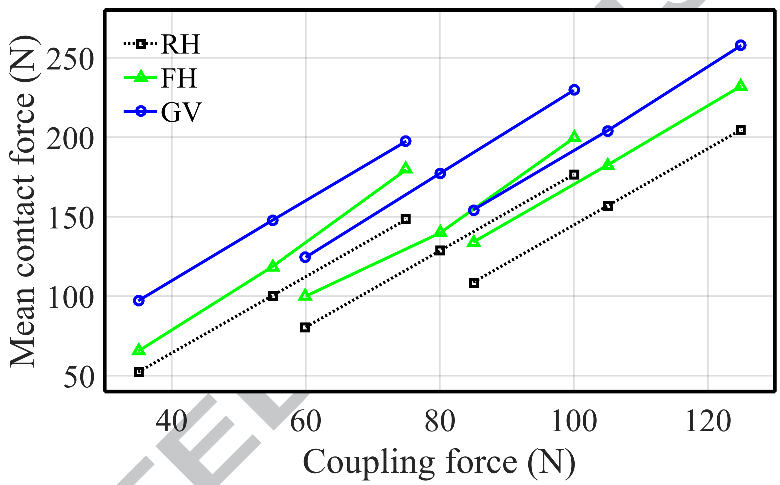


Figure 10. Variations in the contact force with the coupling force obtained for rigid (RH) and viscoelastic contact conditions (FH, GV)

5. Conclusions

The thin and flexible resistive hand sensor showed good linearity and repeatability for measurement of the contact force with relatively small hysteresis and drift. The relationship between the contact force developed by the bare hand grasping a rigid handle with applied hand grip and push forces revealed very good agreements with those reported in the published studies. The proposed sensor design was thus considered for feasible for measurements of the hand contact force developed at the curved tool handle surface. The contact force developed by the bare hand grasping a tool handle enveloped by a viscoelastic vibration absorbing material or the hand grasping a rigid handle via an anti-vibration glove also revealed similar linear dependence on both the grip and push forces. The results showed contact force to be a linear combination of grip and push forces, where the influence of grip force is nearly three times larger than the influence of push force regardless of hand-handle conditions. The grip and push force coefficients for the handle covered by viscoelastic material, however, were about 27.5% and 24% higher when compared to the rigid handle condition considering the same handle size. The contact force developed at the interface of the anti-vibration glove and the hand was also considerably higher compared to the bare hand grasping the handle but only slightly higher compared to the handle with a viscoelastic material. The viscoelastic interface attributed to the handle covering or the glove contributed to the higher hand-handle contact area and mean contact pressure, which contributed to the higher contact force. Working with anti-vibration gloves or tool handles with visco-elastic coverings would thus impose considerably greater grip strength demand on the operators in order to achieve target hand grip and push forces, when compared to the bare hand grasping a rigid handle with the same grip and push forces. The measurement method developed in this study can be used to obtain direct measurements of force/pressure distribution on the gloved hand coupled with a tool handle, and to evaluate the effect of contact force on the vibration exposure.

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- A new sensor is reliable for pressure measurement at a viscoelastic interface
- The sensor has low hysteresis and drift, good linearity and repeatability
- It can measure interface pressure to estimate contact forces on curved surfaces
- Relationships between hand forces are obtained for bare and gloved hand on a handle
- Higher grip strength demand was shown for a gloved hand compared to a bare hand