Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
International Journal of Industrial Ergonomics 34 (2004) 507–518
International Journal of Industrial Ergonomics
www.elsevier.com/locate/ergon

# An investigation on the relationship between grip, push and contact forces applied to a tool handle

D. Welcome[a,*], S. Rakheja[b], R. Dong[a], J.Z. Wu[a], A.W. Schopper[a]

[a]*Engineering & Control Technology Branch, NIOSH, 1095 Willowdale Road, MS 2201, Morgantown, WV 26505, USA*
[b]*Concordia University, Montreal, Canada*

Received 21 February 2003; accepted 21 June 2004
Available online 17 August 2004

**Abstract**

Owing to the strong dependence of the health risks associated with vibration exposure of the human hand and arm on hand force, a laboratory study was conducted to develop a methodology for measurement of the contact force at the tool handle–hand interface, and to identify the relationship between the contact force and the hand grip and push forces. A simulated tool handle fixture was realized in the laboratory to measure the grip and push forces using compression/extension force sensors integrated within the handle and a force plate, respectively. The contact force was derived through integration of the interface pressure over the contact area. These were measured using a capacitive pressure-sensing grid. The measurements were performed with 10 male subjects and three circular cross-section handles of different sizes under different combinations of grip and push forces. The hand–handle interface pressure data were analyzed to derive the contact force, as functions of the constant magnitudes of the grip and push forces, and the handle size. The results suggest that the hand–handle contact force is strongly dependent upon not only the grip and push forces but also the handle diameter. The contact force for a given handle size can be expressed as a linear combination of grip and push forces, where the contribution of the grip force is considerably larger than that of the push force. The results further suggest that a linear relation can characterize the dependence of the contact force on the handle diameter. The validity of the proposed relationship is demonstrated by evaluating the magnitudes of errors between the estimated contact forces with the measured data for the range of handle diameters, and grip and push forces considered in the study.

**Relevance to industry**

The methodology proposed in this study can be applied to measure the effective hand–handle contact force at workplaces for assessing the health risks associated with exposure to hand-transmitted vibration exposure and hand–wrist cumulative trauma. The relationship proposed in the study could be effectively applied for estimating the hand–handle contact force from known grip and push forces that are conveniently and directly measurable in laboratory studies involving vibration analyses of the human hand, power tools and relevant vibration attenuation

*Corresponding author. Tel.: +1-304-285-6334; fax: +1-304-285-6265.
*E-mail address:* zzw8@cdc.gov (D. Welcome).

0169-8141/$ - see front matter 
doi:10.1016/j.ergon.2004.06.005

devices. It is expected to be most useful in field applications, where it could provide an estimate of the range of magnitudes of the hand-grip force applied to the handle of an actual tool, which is quite difficult and expensive to measure. The relationship is also expected to contribute to the on-going standardization efforts for defining a correction factor to account for the effects of hand force on the vibration transmission and hand injuries.


*Keywords:* Hand force; Hand–arm vibration; Hand–handle contact force; Tool handle; Grip force; Push force; Hand coupling force; Hand–handle contact pressure

## 1. Introduction

The variations in contact force between the hand and a vibrating tool handle affect the nature of vibration transmitted to human hand–arm system, and the stresses imposed on the anatomical structure of the system. Many studies have suggested that the magnitude of the hand force imparted on a vibrating tool handle affects the severity of exposure to the hand–transmitted vibration and hand–wrist cumulative trauma disorders (Fransson and Winkel, 1991; Pyykkö et al., 1976; Radwin et al., 1987). The hand force may also have a synergistic effect with vibration exposure on anatomical structures, such as the vascular system, nerves and joints. The assessment of health and safety risk associated with exposure to hand-transmitted vibration, as defined in the current standard (ISO-5349-1, 2001), is solely based upon amplitude, frequency and duration of vibration exposure, while the contribution due to the hand force is ignored. Owing to the strong dependence of the hand–arm responses on the hand force, the need to measure the hand force has been recognized by many investigators, and an international draft standard (ISO/WD 15230, 2000) has been proposed specifically for the hand force measurement. The CEN-12349 (1996) and the recent revision of the ISO-5349-1 (2001) also emphasize the need for measurement of the hand force. These standards, however, provide no guidance regarding the techniques that can be used for the hand force measurement. This is most likely attributed to lack of a reliable measurement methodology.

It has been suggested that the hand force be considered as a weighting factor to account for its contribution in the risk associated with the vibration exposure (Reidel, 1995; Kaulbars, 1996). This requires identification of quantitative relationships between the hand force, the vibration transmission and health effects. Moreover, a consistent definition and a measurement method for the hand force would be needed. Several studies (Iwata et al., 1972; Pyykkö et al., 1976; Reidel, 1995; Hartung et al., 1993; Gurram et al., 1995; Miyashita et al., 1990) have investigated the relationships between the hand force and different measures of the hand–arm responses to vibration. The reported studies on biodynamic response of the human hand and arm to hand-transmitted vibration suggest that an increase in the hand force yields an increase in the magnitude of the response (Iwata et al., 1972; Pyykkö et al., 1976; Gurram et al., 1995). The hand force in these studies is considered either as the grip force or the push force. The grip force $F_g$ is the clamp-like force exerted by the hand when enclosing a handle, which is compensated within the hand by a gripping action acting in the opposite direction towards a dividing plane (Fig. 1). The push force $F_p$ is the force exerted by the hand away from the operator's shoulder towards the work surface, which is not compensated within the contacting surface of the hand. On the basis of laboratory measurements performed on 10 male subjects,

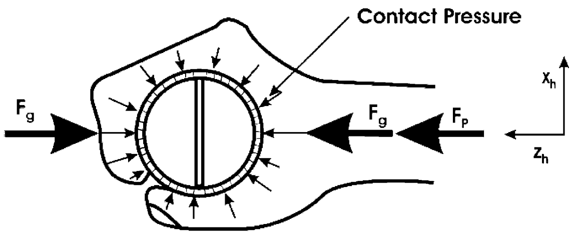


Fig. 1. Definitions of the grip, push and contact forces.

Hartung et al. (1993) showed that the magnitude of vibration transmitted from a vibrating handle to the wrist increases considerably with increasing the grip and push forces. The increase also resulted in higher frequency of the peak vibration transmissibility. Higher grip and push forces further yield increased electrical activity of the m.flexor carpi ulnaris and finger-flexor muscles, and reduced peripheral circulation of fingers (Hartung et al., 1993; Gurram et al., 1995; Miyashita et al., 1990). Reidel (1995) investigated the influence of grip and push forces on the acute reaction of the hand-arm system under vibration exposure in terms of biodynamic response, shifts in vibration perception threshold and subjective vibration sensation. The conclusions of the study were similar to those reported earlier (Iwata et al., 1972; Pyykkö et al., 1976; Gurram et al., 1995; Hartung et al., 1993).

The hand force in all of the above-referred reported studies has been invariably measured in terms of grip and push/pull force components, using split handle designs and force plates, respectively. It is anticipated that these hand force components will continue to be used in further studies of vibration transmission and health effects due to the ease of their measurement and control with high degree of accuracy and repeatability in a laboratory setting using a dynamometer and/or other force measuring devices. While the push force component may be easily measured with real tools in a workplace, the measurement of grip force component with real tools is extremely complex and costly. On many typical power hand tools such as chipping hammers and riveters, it would likely be impossible to implement the split handle designs for the grip force measurement without using a customized tool handle. In addition, the instrumentation for the grip force measurement on many tools handles may also alter the nature of the transmitted vibration. Therefore, it is required to build a 'bridge' that can link the grip and push forces to a practically measurable hand force parameter.

The resultant hand contact force, the sum of the distributed normal force at the hand–handle interface surrounding the handle shown in Fig. 1, may be considered as a good measure of the hand force. It may be directly correlated with the hand-transmitted vibration. Thin-film resistive or capacitive flexible sensors can be effectively used to measure the resultant hand force. The application of such sensors on a real tool handle would be relatively less complex than the measurement of the grip force. These sensors have been successfully applied for qualitative measurement of hand–handle interface pressure distributions (Fellows and Freivalds, 1989; Gurram et al., 1995). The total contact force could be theoretically derived from the contact pressure distribution and the effective contact area. The grip and push forces are simply the summation of the vector projections of the distributed contact force components on a specific axis of the handle at two different sides of the handle, as also shown in Fig. 1. A definite relationship between the effective hand contact force and the grip and push force components therefore should exist. This relationship could serve as the vital 'bridge' that links the laboratory results with their field applications. Such a relationship would permit the estimation of the total hand contact force from the grip and push forces that are widely measured in the laboratory studies, if the contact force could be proven as a better measure of the hand force for assessing the risks associated with exposure to hand-transmitted vibration and other hand injuries.

The specific aims of this study are (i) to develop a methodology based on a capacitive pressure-sensing matrix to measure the total hand–handle contact force for different sizes of circular cross-section tool handles; (ii) to investigate the influence of directly measurable grip and push force components, and the handle diameter on the contact force; and (iii) to derive a relationship between the total hand contact force and the grip and push force components as a function of the handle diameter.

## 2. Methods

A test fixture, comprising an instrumented handle and the mountings, was designed to perform measurements of grip, push and contact forces. Three handles of circular crosssection (30, 40 and 48 mm diameter), split along the length, were developed and instrumented to measure the hand grip force on the basis of the design outlined in ISO-10819 (1996). Two force sensors (Kistler 9212) were integrated within each split handle and the grip force was derived from the sum of the two force signals. The calibration data revealed linear force measuring characteristics of the handles in the 0–100 N range, irrespective of the position of the applied load along the span of the handle. Each handle was installed on an electro-dynamic shaker in a horizontal plane to permit gripping of the handle along the $Y_h$-axis using a mounting bracket, as shown in Fig. 2. It should be noted that the shaker was merely used to provide a support for the test handle, since the concerned forces are measured under static condition alone. The push force imparted by a subject on the mounted handle was measured using a force plate (Kistler 9286AA). Both the push and grip forces were conditioned and displayed on computer screens for monitoring and control purposes. The refresh rate of the displays was set at 1 sample/s.

The EMED measurement system, developed by *NOVEL Electronics*, was used to measure the hand–handle interface contact pressure distribution. The measurement system included a capacitive thin-film pressure sensing grid, and a Pliance mobile data conditioning and acquisition system. The sensing grid, consisting of $16 \times 11$ (16 rows and 11 columns) pressure sensors encased within a 2-mm thick elastomeric mat, was applied to the handle for measuring the hand–handle interface pressure distributions over the contact region. Each sensor covered an area of 0.766 $cm^2$, including the spacing between the adjacent sensors. The sensing mat was calibrated under a pneumatic bladder in the 0–30 $N/cm^2$ range. The sensing mat was wrapped around the handle with an adhesive tape, as shown in Fig. 3. Selected numbers of rows in the sensing grid were masked to ensure that overlapping of active sensors did not occur on smaller diameter handles. The 30 and 40 mm diameter handles required masking of 4 and 2 rows, respectively, of the sensing matrix, while no masking was needed for the 48 mm handle. With the mat applied, the undeformed diameters of the three handles were measured as 36, 44 and 52 mm.

A total of 10 male subjects were employed in the study. Table 1 summarizes the age, height and hand sizes of the test subjects, where the dimensions of the dominant right hands were measured as shown in Fig. 4. The hand volume was measured using the water displacement method. The hand size of each subject was further derived in accordance with EN-420 (1994), which varied from 8 to 11 with mean being 9. With regards to the anthropometric data reported from several studies of US military personnel, the hand size of the test subjects would lie between the 75th and

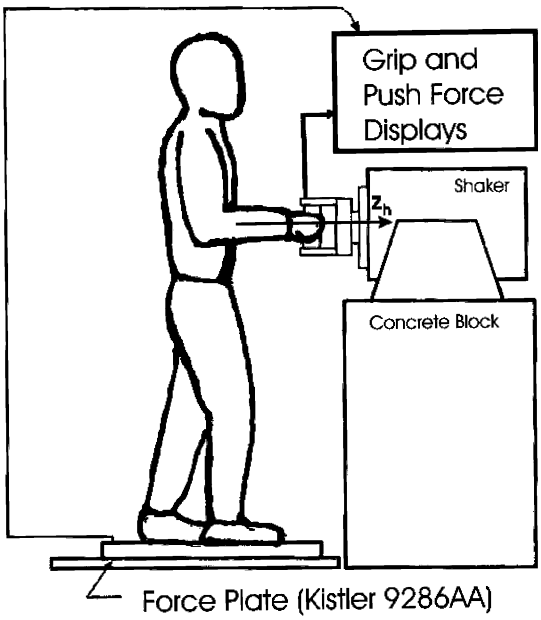


Fig. 2. A schematic of the experimental setup.

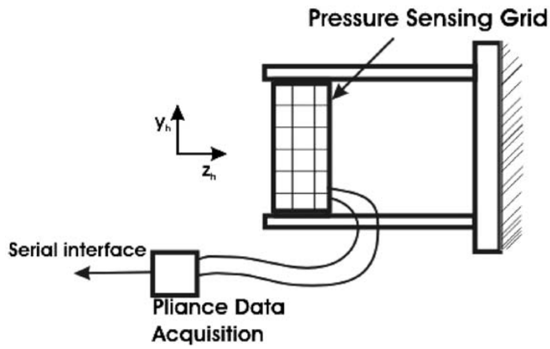


Fig. 3. Pressure sensing mat wrapped around a test handle.

Table 1
Age, height, weight and hand sizes of the test population

| | Minimum | Maximum | Mean | Std. Deviation |
|---|---|---|---|---|
| Age (yr) | 18 | 60 | 29.5 | 14.8 |
| Height (m) | 1.73 | 1.90 | 1.83 | 0.05 |
| Weight (kg) | 64 | 127 | 84.2 | 17.8 |
| Hand length (cm) | 17.5 | 22.0 | 19.6 | 1.2 |
| Hand circumference (cm) | 20.5 | 25.0 | 22.3 | 1.4 |
| Overall hand width (cm) | 10.5 | 12.0 | 11.0 | 0.5 |
| Hand thickness (cm) | 4.5 | 5.5 | 4.9 | 0.4 |
| Hand volume ($cm^3$) | 345 | 525 | 424 | 55 |
| Hand size (EN 420) | 8 | 10–11 | 9 | — |

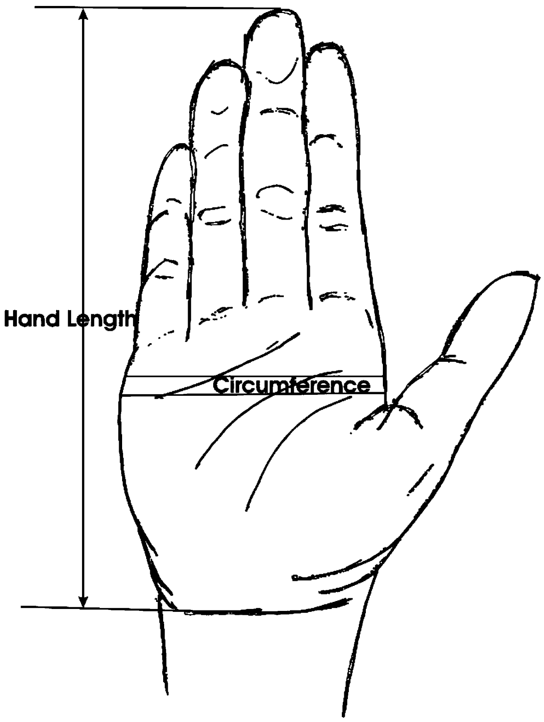


Fig. 4. Dimensions of the subjects' hands.

90th percentile (NASA, 1978). The measurements were performed without the presence of handle vibration to study the relationship between the static grip, push and contact forces. Each subject was advised to stand on the force platform and grasp the installed instrumented handle with his dominant right hand with a specified arm posture (elbow angle = 90° ± 10°), as shown in Fig. 2. The platform height was adjusted to ensure horizontal lower arm and 0° shoulder abduction. The subjects were instructed to maintain specified grip and push forces to their best ability using the visual displays of both the forces. The contact pressure data were acquired for a duration of 7 s after the subject had assumed steady values of grip and push forces. The subject was instructed to take a brief rest for approximately 30 s between successive measurements.

The experimental design for each subject was a three-factor factorial type. The factors included handle diameter with three levels (30, 40 and 48 mm), grip force with five levels (0, 15, 30, 50 and 75 N) and push force with four levels (0, 25, 50 and 75 N). Each subject received brief training on the test procedure and was permitted a number of practice runs prior to the measurements. The measurements with different handles were performed on different days and the order of the specified grip and push forces were randomized for each subject. Each test was performed twice and the data obtained in terms of contact force and contact area were examined to verify repeatability.

### 2.1. Data analysis

The hand–handle contact pressure distribution was analyzed using the EMED software, which computed the total contact force through integration of the local pressure over the effective contact area. The effective contact area was defined as the area covered by sensors with pressure values exceeding a threshold value of 0.286 N/cm$^2$. The threshold value was chosen at this level to minimize electrical background noise in the zero grip and zero push condition. Since each sensor area is constant, assuming uniform pressure over the small sensor area the contact force $F_c$ can be estimated from

$$F_c = \Delta A \sum_{i=1}^{n} p_i, \quad (1)$$

where $\Delta A = 0.766\,\text{cm}^2$ is the sensor area, $p_i$ is pressure measured by sensor $i$ and $n$ is the number of active sensors.

The subject's hand position with respect to the sensing grid on each handle was marked during the first test and the subject was advised to use the same position in subsequent tests. The contact condition corresponding to 0 N grip and 0 N push force was realized by lightly grasping the handle covered by the sensing grid, while monitoring the grip and push force displays. The sensing mat, in general, resulted in a contact force in the 1–15 N range under this condition. This was attributed to the subject-related factors, and hysteresis and offset of the sensing mat, and was treated as a bias in the measured signals.

The data acquired for 10 subjects and 2 trials were analyzed to derive the mean and standard deviation values of the contact force and area corresponding to each grip and push force, and handle size combination. The data attained for two trials revealed very good repeatability in terms of the contact force and contact area, but considerable variation in the peak pressure, which was attributed to variations in the hand's position and inconsistency in localized pressure imparted by the hand.

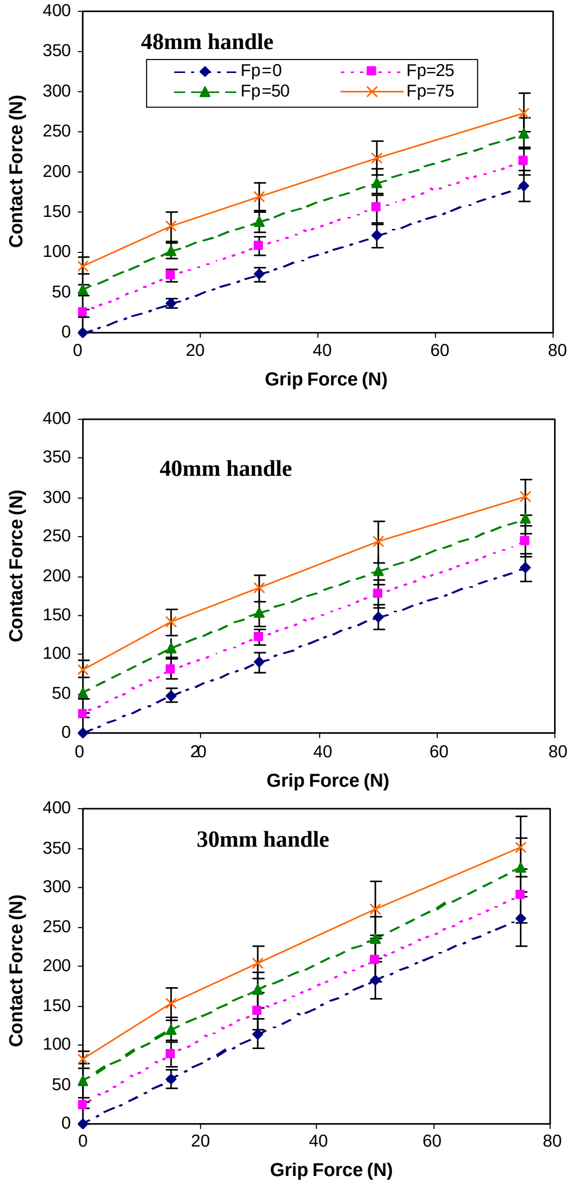


Fig. 5. Variations in mean contact force as a function of the grip force under different levels of constant push force.

## 3. Results and discussion

Fig. 5 illustrates the mean contact force of 10 subjects, derived from integration of the localized pressure over the hand–handle contact area, as a function of the grip force. The mean values are presented corresponding to each of the four constant magnitudes of push force and handle diameter. The results show relatively small inter-subject variability as evidenced by the magnitude of the error bars, denoting the standard deviation of the contact force data. The coefficients of variation of the measured data were observed to vary in the 10–20% range for the 30 mm diameter handle, and 7–18% range for the 40 and 48 mm handles. The results show a linear dependence of the contact force on the grip force, irrespective of the push force magnitude and handle size. The correlation coefficients ($r^2$: the square of the sample correlation coefficient) of all of the linear fits were greater than 0.99, and higher order fits were deemed unnecessary for practical simplicity. The variations in the push force tend to cause a nearly constant shift in the contact force for all handle sizes, as shown in the figure. The magnitude of this shift corresponding to a given push force is quite similar to the push force magnitude, suggesting its direct contribution to the contact force. The magnitude of the contact force and its rate of change with respect to the grip force vary significantly with the handle diameter, as is evident from the slopes of the curves attained for three handle sizes. The contact force developed between the hand and a smaller diameter handle (30 mm) is considerably larger than that attained with the larger diameter handles. This is mostly attributed to more uniform distribution of high pressures with smaller size handles. The slopes of the curves, however, are quite similar within a given handle size.

Fig. 6 illustrates the variations in the mean contact force with varying push force corresponding to different handle sizes and magnitudes of grip force. The results again show a linear dependence of the contact force on the push force, irrespective of the grip force magnitude and the handle size. Again, the correlation coefficients ($r^2$) of all of the linear fits were greater than 0.99, and higher order fits were deemed unnecessary. The variations in the grip force also cause a nearly constant shift in the contact force for all handle sizes. Unlike the results shown in Fig. 5, the magnitude of the shift is considerably larger for small size handles. The rates of change of contact force with respect to the push force remain comparable for all handle sizes, further suggesting almost direct dependence of the contact force on the push force, irrespective of the handle size.

A three-factor repeated measures analysis of variance (ANOVA) was performed on the bias

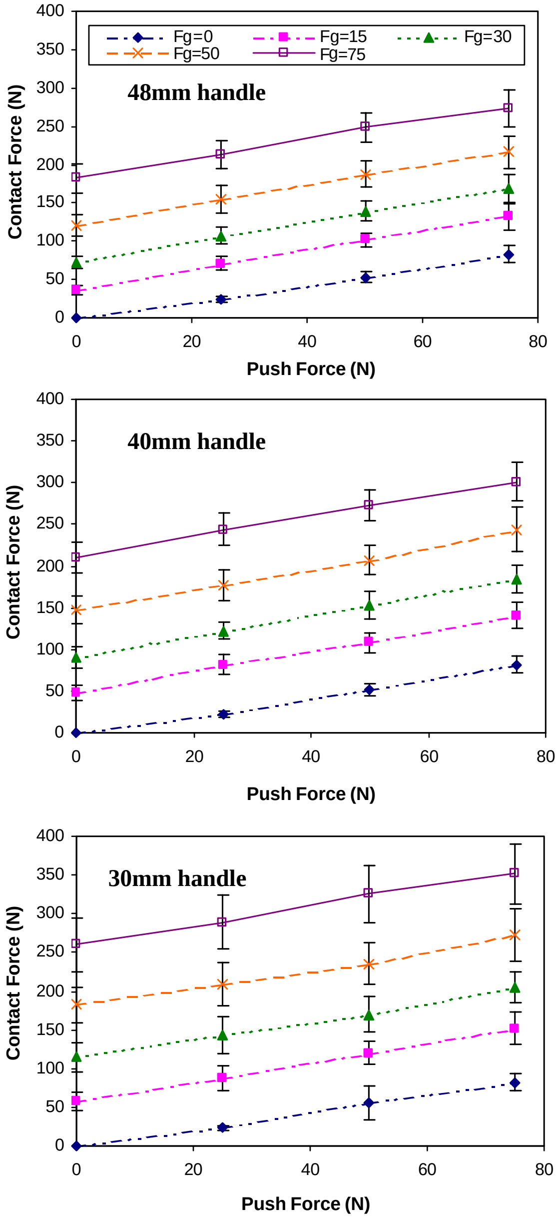


Fig. 6. Variations in mean contact force as a function of the push force under different levels of constant grip force.

removed data using SPSS version 10. The factors represented the three nominal diameters of the handles, the four levels of push force and the five levels of grip force. Based on a preliminary analysis using Mauchly's Test of Sphericity, the conservative Greenhouse–Giesser (1959) probabilities were used to characterize the reliability of the findings. The ANOVA of the mean unadjusted contact force revealed reliably significant results for all three main factors ($p<0.001$)—handle diameter, and grip and push force. The analysis also revealed significant handle-diameter-by-grip-force ($p<0.001$) and push-by-grip interactions ($p<0.05$).

The variation in the contact force $F_c$ is further examined with respect to the coupling force as defined by Reidel (1995) and Kaulbars (1996), and expressed in Eq. (2).

$$F_{cou} = F_g + F_p. \quad (2)$$

From Figs. 5 and 6, it is evident that magnitude of the contact force is far more dependent upon the grip force than the push force, while the coupling force definition implies equal significance of both the grip and push forces. Considering that a specific value of coupling force can be attained through many different combinations of grip and push forces, variations in the contact force with coupling force would be nonlinear. Fig. 7 illustrates the normalized mean contact force ($F_c/F_{cou}$) as a function of the coupling force for different magnitudes of grip force. The results show nonlinear dependence of the contact force on the coupling force for all the handle sizes considered. It is evident that the hand–handle contact force could be as high as 4 times the coupling force for a 30 mm handle. This peak ratio reduces to nearly 3.2 for 40 mm handle and 2.4 for the 48 mm handle. The normalized contact force, however, approaches to lower values as the push force contribution in the coupling force increases. Larger magnitudes of grip force yield considerably higher values of the normalized contact force, further indicating stronger dependence on the grip force. These results suggest that the coupling force does not characterize the hand–handle contact condition for assessment of vibration-induced risks to the human hand.

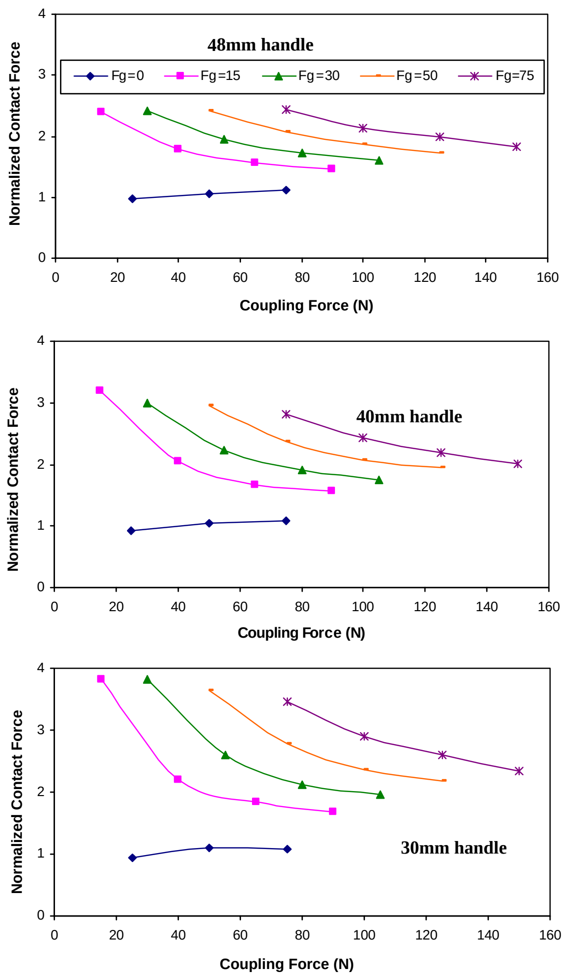


Fig. 7. Normalized contact force as a function of the coupling force under different constant magnitudes of grip force.

### 3.1. Relationship between $F_c$, $F_g$ and $F_p$

The results presented in Figs. 5 and 6 suggest that the contact force is strongly dependent upon not only the grip and push forces, but also the handle diameter. The dependence of $F_c$ on $F_g$ and $F_p$ alone, however, can be described by a linear function. For a given handle diameter, a relationship between the $F_c$, $F_g$ and $F_p$ may thus be expressed as:

$$F_c = \alpha(D)F_g + \beta(D)F_p, \quad (3)$$

where $\alpha(D)$ and $\beta(D)$ are functions of effective handle diameter $D$, describing the relative contributions due to $F_g$ and $F_p$, respectively, to the total contact force. It should be noted that the elastomeric pressure-sensing mat wrapped around the handle increases its effective diameter. Assuming 50% deformation of the elastomer, the model coefficients are derived for effective handle diameters of 33 (partial overlap of mat), 42 and 50 mm, respectively, for the 30, 40 and 48 mm handles. A linear curve-fit is performed to identify the constant coefficients for each handle size, which are presented in Table 2. The coefficient values reveal that the contribution of the grip force to the total contact force is far more significant than that of the push force. The contact force estimated from the proposed relationship is compared with the measured data to examine its validity for each handle size. Fig. 8 illustrates the errors between the measured and estimated contact forces normalized with respect to the measured data for entire range of grip and push forces considered in the study. The results reveal errors in the range of 3–14% corresponding to grip force exceeding 15 N for all the handles. The proposed model, however, exhibits high magnitude of error corresponding to light grip and push conditions, possibly attributed to subjects' inability to maintain 0 N grip while grasping the handle, and hysteresis and offset associated with the elastomeric pressure sensors. The peak errors corresponding to 0 N grip approach as high as 16% for the 30 mm handle, 18% for the 40 mm and 16% for the 48 mm handle. The magnitude of this error tends to be high for 25 N push force and decreases considerably as the push force increases. The peak error corresponding to 75 N push and 0 grip force reduces to well below 3%. With the exception of relatively large error corresponding to 0 N grip and 25 N push force, the results show that the contact force can be effectively predicted from the directly measurable grip and push forces.

Table 2
Model coefficients characterizing contact force dependence on the grip and push forces

| Nominal handle diameter (mm) | Effective handle diameter (mm) | $\alpha(D)$ | $\beta(D)$ |
|---|---|---|---|
| 30 | 33 | 3.56 | 1.08 |
| 40 | 42 | 2.87 | 1.10 |
| 48 | 50 | 2.43 | 1.12 |

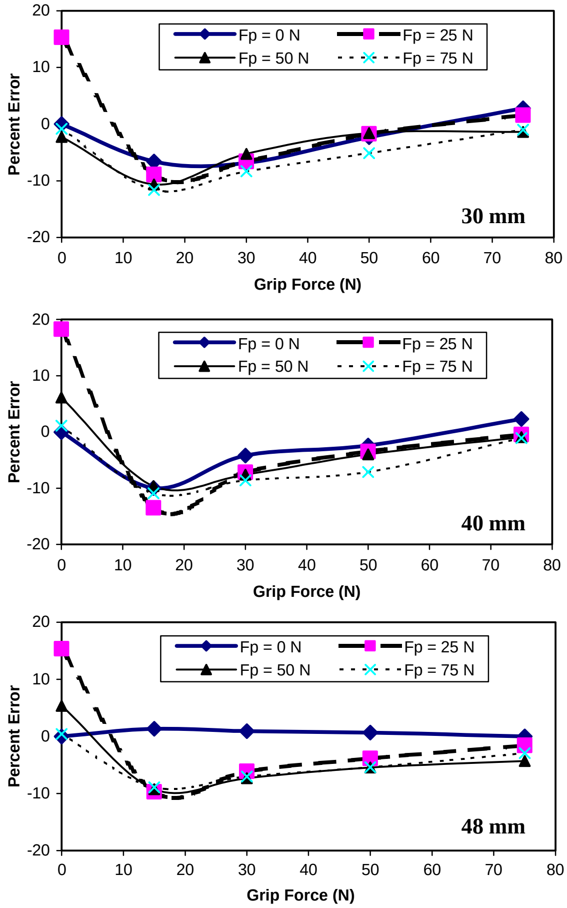


Fig. 8. Magnitudes of errors between estimated and measured contact forces as a function of the grip force under different magnitudes of push force.

The coefficient values further show that the contact force tends to diminish as the handle diameter increases. The contact force dependence on the grip force also tends to decrease more rapidly with the handle size, while its sensitivity to push force appears to be relatively small when handle diameter is increased from 30 to 48 mm. These variations in dependence of the contact force on the grip and push forces for different handle sizes are attributed to changes in the contact area and hand–handle interface pressure in a complex manner. Fig. 9 illustrates the effective hand–handle contact area as a function of the grip and push forces for all three handle sizes. The

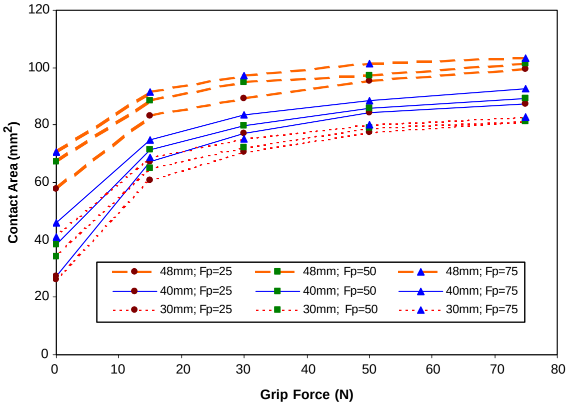


Fig. 9. Effective contact area as a function of the handle size, and grip and push forces.

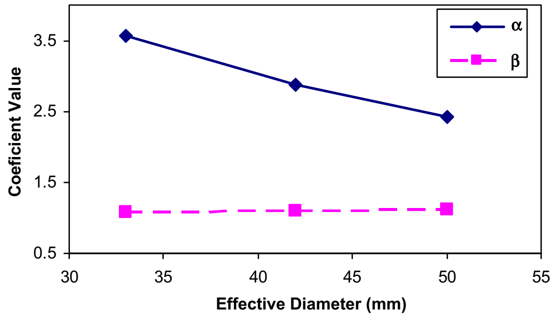


Fig. 10. Variations in model coefficients with respect to effective diameter.

contact areas tend to rapidly approach nearly steady values as the grip force exceeds 15 N, irrespective of the handle size. The 48 mm handle yields the maximum steady value of the contact area, while the 30 mm yields the lowest value. Considering that the contact force is a function of the effective contact area and magnitudes of interface pressure, the high contact force developed with the 30 mm diameter would suggest the presence of relatively high interface pressures. Higher push forces yield slightly larger contact area, irrespective of the handle size and the grip force.

The variations in the model coefficients $\alpha(D)$ and $\beta(D)$ with respect to the handle size are further illustrated in Fig. 10. The curve-fittings performed on the data show that the diameter dependence can be described by the following linear functions ($r^2 > 0.99$):

$$\alpha(D) = -0.0667D + 5.7327, \quad 30\text{ mm} \leqslant D \leqslant 50\text{ mm}, \tag{4}$$

$$\beta(D) = 0.0024D + 1.0021, \quad 30\text{ mm} \leqslant D \leqslant 50\text{ mm}, \tag{5}$$

where $D$ is in mm.

Eqs. (3)–(5) fully describe the relationship between the grip, push and contact forces. A comparison of the values of contact force derived from the above model attained under different combinations of handle size, and grip and push forces with the measured data revealed peak errors below 9% for grip force exceeding 15 N and in the order of 20% for 0 grip condition, as observed earlier for all three handle sizes. The peak error in the vicinity of 0 N grip occurs for 25 N push and decreases to nearly 12% for 75 N push force. Eqs. (3)–(5) are applied to study the variations in hand–handle contact force as a function of the handle size for various magnitudes of grip and push forces. The results presented in Fig. 11 suggest that for given values of push and grip forces a smaller diameter handle, despite its lower effective contact area (Fig. 9) would yield higher contact force. A smaller handle would thus yield considerably higher interface pressure.

From the comparison of the measured contact force with the hand–handle coupling force, as defined in the literature and the ISO working document, it is concluded that the contact force varies nonlinearly with the coupling force. The hand–handle contact force could be as high as 4 times the coupling force for a 30 mm handle, 3.2 times for the 40 mm and 2.4 times for the 48 mm handle. It is thus concluded that the coupling force does not characterize the hand–handle contact condition for assessment of vibration-induced risks to the human hand. Moreover, it is quite difficult to measure grip force on real tools in a workplace in order to derive the coupling force, as defined in other studies and the ISO document. The practical implementation of the coupling force for real tools may thus pose considerable challenges. The proposed contact force and the

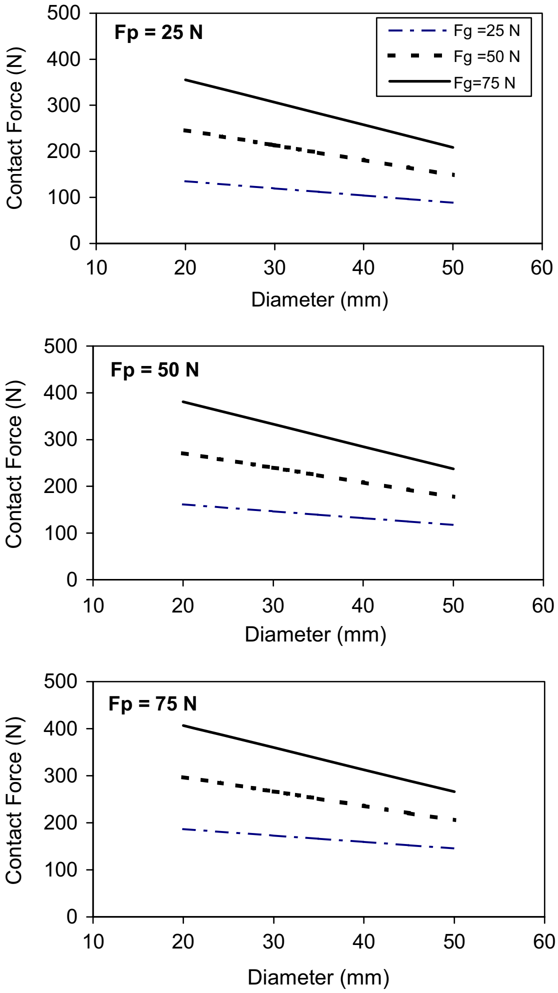


Fig. 11. Dependence of hand–handle contact force on the effective handle diameter.

relationship, on the other hand, could provide an accurate estimate of the grip force magnitude for a range of cylindrical handle sizes considered in this study.

## 4. Conclusions

It has been established that the severity of the risk posed by exposure to hand–tools vibration increases considerably with increasing hand–tool contact force. Reliable methods, however, do not yet exist for measurement of the contact force, specifically for applications involving tool handles of complex geometry and field trials. A method for measuring the hand–handle contact force is proposed and evaluated. The contact force applied at the hand–handle interface was measured using a thin-film capacitive pressure-sensing grid under different combinations of grip and push forces, and handle sizes. The measured data were analyzed to identify a relationship among the contact, grip and push forces as a function of the handle diameter. From these analyses it is concluded that the contact force and the contact area can be effectively measured using the pressure-sensing grid.

The results suggested that the contact force is linearly dependent upon the grip and push forces and handle diameter. The hand–handle contact force for a given handle size could be derived from a linear combination of the grip and push forces, where the contribution due to grip force is considerably larger. The variations in push force tend to cause a constant shift in the contact force over the entire range of grip forces. The rate of change of contact force with respect to push force was observed to be comparable for all handle sizes, suggesting that the contact force is relatively less sensitive to handle size when a constant grip force is considered. The rate of change of contact force with respect to grip force, however, tends to be considerably higher for smaller handles. Analysis of the measured effective contact area suggests that the largest handle considered in this study (48 mm) yields larger effective contact area. The effective contact areas for all the handles rapidly approached to nearly steady values as the grip force exceeds 15 N.

The dependence of the grip force and thus the contact force on the handle diameter can be accurately described by a linear function in handle diameter. A relationship is formulated to characterize the hand contact force on the basis of the linear combination of grip and push forces in conjunction with linear variations in the handle size. The contact forces estimated from the proposed relationship agree very well with the measured data, with the exception near 0 N grip force. High degree of error near 0 N grip is attributed to subjects' inability to maintain 0 N grip while grasping the handle, and hysteresis and offset associated with the elastomeric pressure sensors. The proposed relationship is thus considered to be valid for the ranges of handle sizes, and grip and push forces considered in the study. The smaller handle (30 mm), despite its lowest contact area, yields the highest magnitude of contact force, which suggests that a smaller diameter handle would cause considerably higher values of hand–handle interface pressure. The dependence of contact force on the handle diameter in view of the associated health risks would require further studies on the localized pressure peaks.

## Acknowledgements

The authors wish to thank Kiran Kunderu, Brad Westfall, and Chris Warren for their assistance in this study.

## References

CEN-12349, 1996. Mechanical vibration—guide to health effects of vibration on the human body. European Committee for Standardization.

EN-420 European Committee for Standardization, 1994. General requirements for gloves. European Committee for Standardization.

Fellows, G.L., Freivalds, A., 1989. The use of force sensing resistors in ergonomic tool design. Proceedings of the 33rd Annual Meeting of the Human Factors Society, pp. 713–717.

Fransson, C., Winkel, J., 1991. Hand strength: the influence of grip span and grip type. Ergonomics 34 (7), 881–892.

Greenhouse, S.W., Geisser, W., 1959. On methods in the analysis of profile data. Psychometrika 24, 95–112.

Gurram, R., Rakheja, S., Gouw, G.J., 1995. A study of hand grip pressure distribution and EMG of finger flexor muscles under dynamic loads. Ergonomics 38 (4), 684–699.

Hartung, E., Dupuis, H., Scheffer, M., 1993. Effects of grip and push forces on the acute response of the hand-arm system under vibrating conditions. Occupational and Environmental Health 64, 463–467.

ISO-5349-1, 2001. Mechanical vibration—measurement and evaluation of human exposure to hand-transmitted vibration—Part1: General requirements. International Organization for Standardization.

ISO-10819, 1996. Guide for mechanical vibration and shock–hand–arm vibration-method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand. International Organization for Standardization.

ISO/WD 15230, 2000. Definition and guidelines for the measurement of the coupling forces for operators exposed to hand-arm vibration. ISO/TC 108/SC 4/WG 3.

Iwata, H., Dupuis, H., Hartung, E., 1972. Ubertrang von horizontalen sinusschwingungen auf die oberen extremitaten bei halbpronationsstellung und reaktion des m biceps. Internationales Archive for Arbeitsmedizin 30, 313–327.

Kaulbars, U., 1996. Measurement and evaluation of coupling forces when using hand-held power tools. Central European Journal of Public Health 4 (1), 57–58.

Miyashita, T., Miura, H., Futatsuka, M., 1990. Hand-arm vibration, noise, temperature and static load: an experimental study of peripheral circulation while operating chain saws. Kurume Medical Journal 37, 73–83.

NASA-1024, 1978. Anthropometric Source Book Volume II: A Handbook of Anthropometric Data. NASA Reference Publication.

Pyykkö, I., Farkkila, M., Toivanen, J., Korhonen, O., Hyvarinen, J., 1976. Transmission of vibration in the hand-arm system with special reference to changes in compression force and acceleration. Scandinavian Journal of Environment and Health 2, 87–95.

Radwin, R.G., Armstrong, T.J., Chaffin, D.B., 1987. Power hand tool vibration effects on grip exertions. Ergonomics 30 (5), 833–855.

Reidel, S., 1995. Consideration of grip and push forces for the assessment of vibration exposure. Central European Journal of Public Health 3, 139–141.