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Contact pressure distribution at hand–handle interface: role of hand forces and handle size

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Abstract

The distribution of localized pressure peaks and the resulting contact forces over the hand surface are investigated through measurements performed under applications of different combinations of hand grip and push forces in the 0–75 N range. Three different cylindrical handles of 30, 40 and 48 mm are used to measure the hand-induced forces and distributed pressures using a capacitive pressure-sensing mat wrapped around the handle. The data acquired with 10 adult male subjects are analyzed to derive the contact force distributions over the hand surface as functions of the grip and push forces, and the handle size. The peak pressures occurring in different regions of the hand surface are also derived and examined in view of the reported pressure-discomfort and pressure-pain threshold limits. For this purpose, the hand surface is split into five different zones. The results show that contact pressures of considerable magnitudes develop within the hand–handle interface, while the magnitudes of peak pressures strongly depend upon the handle size, grip and push forces. Application of high grip and push forces causes the peak pressures to exceed the discomfort threshold values, specifically for the thenar eminence. The peak pressures attained for the 48 mm handle under moderate levels of grip and push forces exceed the suggested sustained pressure values for the preservation of working efficiency. The results also suggest that the mean peak interface pressure for a given handle size can be expressed as a linear combination of grip and push forces. Furthermore, the proportions of hand–handle contact force developed within individual zones also vary linearly with grip and push forces, and strongly depend upon the handle size. The results show that the contact force developed in the vicinity of proximal phalanges of the digits and the palm is generally attributed to the push force, while forces at the fingers surface are caused by the gripping action. Owing to the difficulties associated with the measurement of interface pressures, the proposed relationships could be conveniently applied to obtain an estimate of the mean values of peak pressures on the basis of directly measurable grip and push forces.

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Relevance to industry

The methodology proposed in this study and the results could be applied to estimate the peak hand–handle interface pressures for operators of hand-held tools, which have been associated with discomfort, pain and musculoskeletal disorders. The suggested methods provide objective means to assess the magnitudes and locations of high pressure peaks that may cause pressure-induced discomfort and pain, and thereby the stresses imposed on the hand. The distribution of pressure and the contact force in the hand–handle interface as a function of the handle size could lead to advancement of knowledge on the handle size issue. Furthermore, the results are expected to enhance our understanding of the biodynamic response of the human hand–arm, while operating power tools.

Keywords: Hand–handle interface pressure distribution; High-pressure zones; Pressure pain and discomfort; Hand–handle contact force; Hand-tools; Estimation of peak pressure; Handle size; Grip and push forces

1. Introduction

Work-related musculoskeletal symptoms and injuries, such as carpal tunnel syndrome, tendonitis and vibration-induced white finger are common among operators of hand-held power tools (Nathan et al., 1988; Nilsson et al., 1993). Operation of some of these tools demands high grip, push or hand–handle contact force, which is known to be one of the primary factors that increase the risk of cumulative trauma disorders (Radwin et al., 1987; Rempel et al., 1992; Reidel, 1995). Many studies have suggested that the contact force between the hand and a tool handle affect the severity of exposure to the hand-transmitted vibration and hand–wrist cumulative trauma disorders (Fransson and Winkel, 1993; Pyykkö et al., 1976; Radwin et al., 1987). The hand–arm responses measured in terms of the biodynamic response, magnitudes of wrist-transmitted vibration, and electrical activity of the m. flexor carpi ulnaris and finger–flexor muscles increase with increasing hand–handle coupling intensity, while the peripheral circulation of fingers decreases (Iwata et al., 1972; Pyykkö et al., 1976; Gurram et al., 1995; Hartung et al., 1993; Miyashita et al., 1990).

Although the above studies have established an association between the magnitude of hand–handle coupling force and various measures of the hand–arm responses, the mechanisms leading to risk of hand–wrist cumulative trauma disorders have not been identified. High contact forces impose high stresses on the anatomical structure of the hand, which may be strongly affected by many factors, such as working posture, weight of the tool, grip and push forces, handle size, individual work habits and hand–handle interface pressure. While the majority of the studies on assessment of hand-tool operators have emphasized the consideration of overall contact force (Reidel, 1995; Kaulbars, 1996; ISO-5349-1, 2001; ISO/WD-15230, 2000); the direct measurement of contact force has not yet advanced for application to power tools (Welcome et al., 2001). Other studies have suggested that the perception of discomfort, fatigue and loss of productivity is related to concentration of localized forces at the hand–handle interface, as opposed to the total contact force (Gurram et al., 1995). Existence of a high pressure on the surface of the hand, arising from grasping and guiding a tool handle, could cause a sense of discomfort or pain under sustained loading, which is often a limiting factor during work and may lead to potential impending tissue damage. Sensitivity of the hand to externally applied pressures has been investigated using an algometer to establish the pressure-discomfort (PDT) and pressure-pain threshold (PPT) (Muralidhar and Bishu, 2000; Fransson-Hall and Kilbom, 1993; Johansson et al., 1999). These studies concluded that the thenar area, the skin fold between the thumb and index finger, and region around os pisiform have low PPT and PDT in relation to the rest of the hand surface. The tips of digits IV and V, and the zone near the fourth metacarpal were also found to exhibit low PDT.

The grasping and guiding of a tool handle yields highly uneven distribution of forces at the hand surface (Gurram et al., 1995), which could vary considerably with hand and handle sizes, push and grip forces, and nature of vibration. Only a few studies have attempted to study the distributed hand forces at the hand–handle interface and their dependence on the handle size, and grip and push forces that could serve as a vital basis for the design of handles. Limited efforts in the area have most likely been attributed to lack of reliable measurement methods. Fellows and Freivalds (1991) applied 14 force-sensing resistors to study the relative distribution of subjects' grip force on wooden (30 mm diameter) and foam-covered (38 mm diameter) handles while performing specified tasks. Gurram et al. (1995) used a total of 20 capacitive sensors to study the hand–handle interface pressure distribution under different magnitudes of grip force and handle vibration. Both studies showed the presence of high-magnitude local forces on the tips of the index and middle fingers, and base of the thumb (thenar eminence). It was further shown that the magnitudes of local forces increase considerably with increasing grip force and their concentration shifts considerably under the presence of vibration (Gurram et al., 1995). The dependence of localized pressure peaks on the hand surface, handle size and push force, however, have not been investigated. Moreover, the limited number of sensors used in these studies would affect the accuracy of the reported quantitative data.

In this study, the hand–handle pressure distributions are acquired for three different diameters of circular cross-section handles, using a 16×11 pressure-sensing grid under different combinations of static grip and push forces. The measured data are analyzed to identify the magnitudes and locations of localized pressure peaks occurring at the hand surface as functions of the handle size and static hand forces (grip and push). The relationships between the peak pressures, and grip and push forces were established for different handle sizes.

2. Materials and methods

A test fixture, comprising an instrumented handle and associated mounting, was designed to perform measurements of hand–handle interface pressure and contact force distributions. Three handles of circular cross-section (30, 40 and 48 mm diameter), split along the length, were developed and instrumented in the NIOSH laboratory to measure the handgrip force. Fig. 1 illustrates the hand forces, such as grip (F_g), push (F_p) and contact (F_c) forces, occurring at the hand–handle interface. Each handle integrated two force sensors (Kistler 9212) and a summing circuit was used to derive the grip force. The calibration data revealed linear force measuring characteristics of the handles in the 0–100 N ranges, 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 Z_h-axis using a mounting bracket. It should be noted that the shaker was merely used to provide a support for the test handle, since the concerned pressure distribution and forces are measured under the static condition alone. The push force imparted on the mounted handle was measured using a force plate (Kistler 9286AA). Both the push and grip force signals were conditioned and displayed on a computer screen at a refresh rate of 1 sample/s for monitoring and control purposes.

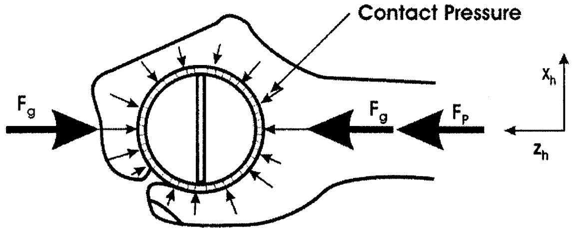

Fig. 1. Definition of grip, push and contact force.

The hand–handle interface contact pressure distributions were acquired at the NIOSH laboratory using the EMED measurement system of *NOVEL Electronics*. The measurement system consists of a flexible capacitive pressure-sensing grid, and a Pliance mobile data conditioning and acquisition system. The sensing grid comprises 16×11 (16 rows and 11 columns) pressure sensors encased within a 2 mm thick elastomeric mat, which was applied to the selected handle, as shown

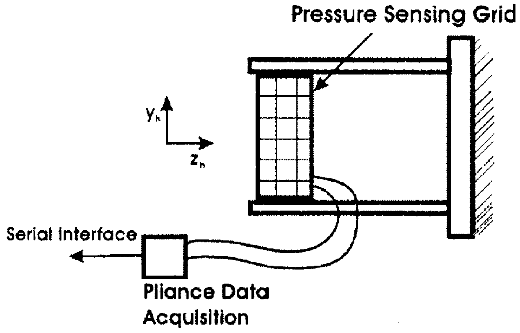

Fig. 2. Pressure-sensing mat wrapped around a test handle.

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

	Minimum	Maximum	Mean	SD
Age	18	60	30.2	4.87
Height (m)	1.77	1.9	1.84	0.04
Weight (kg)	63.5	127	86	17.65
Hand length (cm)	17.5	22	19.68	1.189
Hand circumference (cm)	20	25	22.46	1.331
Overall hand width (cm)	10.5	12	11.05	0.522
Hand thickness (cm)	4.5	5.5	4.88	0.44
Hand volume (cm^3)	345	525	429.6	54
Hand size (EN420, 1994)	9	10–11	9	—

in Fig. 2, 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 overlapping of active sensors encountered with smaller handles was eliminated by masking selected rows of sensors. A total of four and two rows of the sensing matrix were masked for 30 and 40 mm handles, respectively, while no masking was needed for the 48 mm handle.

A total of 10 male adult 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 described in Welcome et al. (2001). The hand volume was measured using water displacement method. The hand size of each subject was further derived in accordance with EN 420 (1994). The pressure measurements were performed with the bare hand under static grip and push conditions. 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 = $90^\circ \pm 10^\circ$). The platform height was adjusted to ensure horizontal lower arm and 0° shoulder abduction. The subjects were advised to maintain specified grip and push forces using the feedback from the visual displays. The measurements were performed under different magnitudes of grip and push forces in the 0–75 N range to study the effect of their variations on the magnitudes and locations of peak pressures. 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 (F_g) with five levels (0, 15, 30, 50 and 75 N) and push force (F_p) 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 was randomized for each subject. Each test was performed twice and the data obtained in terms of contact force were examined for the consistency of the measurement.

3. Data analysis

The hand–handle contact pressure distribution was analyzed using the EMED software, which could also provide the overall peak pressures within specified contact areas. The hand surface was divided into five zones, as shown in Fig. 3, to study the localized peak pressures and contact forces developed within each zone. These zones were identified upon consideration of the hand/handle geometry and the range of hand sizes considered in the study. Zone 1 contains the fingertips of the second, third and fourth digits for the range of hand sizes considered, while zone 2 envelops the tip and middle phalange of the first digit and the middle phalanges of digits II, III and IV. Zone 3 consists of the proximal phalanges of the four digits and the adjacent upper extremity of the palm. Zone 4 generally encompasses the upper

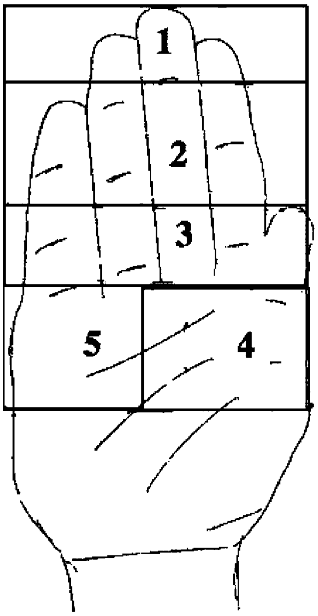

Fig. 3. Hand with five assigned zones.

lateral side of the palm, while the zone 5 in general envelops the upper medial side of the palm. The zone comprising the lower palm and the carpals was excluded, as the contact between this zone and the handles was not observed.

The number of sensor columns within all the zones was identical for all handles; 11 columns in zones 1, 2 and 3, while the zones 4 and 5 comprised seven and four columns, respectively. For all handles and range of hand sizes considered, zones 1 and 3 consisted of three rows (2.625 cm in length—33 sensors in each zone). Zone 2 comprised five rows (4.375 cm in length—55 sensors) for the 48 mm handle, four rows (3.5 cm in length—44 sensors) for the 40 mm handle and three rows (2.625 cm in length—33 sensors) for the 30 mm handle. Zones 4 and 5 comprised five rows for the 48 mm handle (4.375 cm in length—35 sensors in zone 4 and 20 sensors in zone 5), four rows for the 40 mm handle (3.5 cm in length—28 sensors in zone 4 and 16 sensors in zone 5) and three rows for the 30 mm handle (2.625 cm in length—21 sensors in zone 4 and 12 sensors in zone 5). The measurement system also provides the effective contact area, defined as the area enclosed by sensors with pressure values exceeding a threshold value of $0.143\,\mathrm{N/cm^2}$. The contact force developed by the entire surface and individual zones could be derived through integration of the local pressure over the effective contact area. Since each sensor area is constant, assuming uniform pressure over the small sensor area, the contact force F_c (overall and within a zone) can be estimated from

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

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

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 data acquired for 10 subjects and two trials were analyzed to derive the mean and standard deviation (SD) values of the overall and local pressure peaks, and contact force corresponding to each test condition (grip and push force, and handle size combination). The data attained for two trials revealed good repeatability in terms of the contact force, but larger variations in the peak pressures were observed, which were attributed to variations in the hand's position in relation to a particular sensor location within the grid, the hysteresis effect of the pressure sensors and inconsistencies in the localized pressure imparted by the hand.

4. Results and discussion

4.1. Overall contact force and peak pressure

The mean contact force together with SD were obtained from integration of the localized pressure over the entire hand–handle contact area, as a function of the push force corresponding to five constant magnitudes of grip force for different handle diameters, for the 10 subjects considered. The results revealed linear dependence of the contact force on both grip and push forces, and increasing contact force with smaller handle size, as concluded by Welcome et al. (2001) and Marcotte et al. (2003). The overall contact force developed at the hand–handle interface is a function of the interface pressures and the effective contact area, which would depend upon the handle size.

Table 2 summarizes mean values and SD of the hand–handle interface peak pressures observed for the 10 subjects, three handles and different hand force combinations. The table further presents the location of the peak interface pressure (PP) in terms of the contact zones described in Fig. 3. The results show considerable variations in the peak pressure, as evident from high values of SD of the mean peak pressures measured for different subjects under different combinations of the hand forces. Such variations would be expected and are mostly attributed to poor repeatability in the pressure imposed by the hand and differences in geometric location of the pressure hot points in relation to the sensor location. The results, however, show consistent location of the high-pressure zone, irrespective of the hand force combination. The mean peak pressures for all subjects and handles generally lie in zone 4, upper lateral side of the palm in the vicinity of the thenar region, although some exceptions are also observed. For the 48 mm handle, the peak pressures invariably occur in this zone, irrespective of the hand force combination. The peak pressures obtained for the 40 mm handle also show the same trend, except in the absence of the push force, a condition requiring lower pressure from the lateral side of the palm (zone 4). Gripping the handle in this case necessitates application of pressure mostly from the fingers, specifically the fingertips. The location of the peak pressure under such conditions tends to shift to zone 1 comprising the tips of digits 2, 3 and 4, specifically under grip force exceeding 30 N.

Similar trends are also observed for the 30 mm diameter handle, where the peak pressure tends to shift from zone 4 to zone 1 in the absence of the push force. The application of high grip force coupled with light push force, such as push/grip combinations of 25/50 N and 25/75 N, also cause

Table 2
The mean and standard deviation of the peak pressure and its location under various grip/push force levels for different handle sizes

Handle size		48 mm			40 mm			30 mm		
Grip (N)	Push (N)	PP(kPa)	SD	Zone	PP(kPa)	SD	Zone	PP(kPa)	SD	Zone
0	25	45.52	14.56	4	33.07	11.67	4	31.34	16.15	4
	50	68.96	27.09	4	55.36	18.84	4	55.27	20.72	4
	75	99.35	37.11	4	73.57	19.14	4	76.25	28.11	4
15	0	46.10	22.15	4	36.21	11.85	4	51.25	21.75	1
	25	79.22	30.99	4	62.21	21.15	4	61.79	32.12	4
	50	95.84	29.91	4	82.64	19.27	4	90.00	37.28	4
	75	124.94	35.96	4	104.93	26.15	4	104.37	34.23	4
30	0	62.40	19.88	4	56.00	21.23	1	81.52	20.82	1
	25	91.10	22.11	4	75.79	26.36	4	79.37	40.89	4
	50	112.66	33.56	4	102.14	28.43	4	104.64	48.77	4
	75	144.03	48.00	4	116.93	22.07	4	129.11	45.93	4
50	0	88.38	23.81	4	83.57	20.20	1	110.09	24.41	1
	25	114.42	36.20	4	102.57	31.76	4	100.45	21.37	1
	50	144.16	38.83	4	123.43	33.24	4	117.68	37.62	4
	75	161.62	50.58	4	141.64	31.48	4	146.61	42.11	4
75	0	127.99	36.41	4	111.57	21.76	1	135.62	21.33	1
	25	154.03	39.76	4	121.71	24.98	4	141.07	42.55	1
	50	173.31	42.43	4	149.57	29.79	4	145.98	24.67	3
	75	198.12	52.16	4	156.07	28.87	4	168.30	48.94	4

peak pressure to shift from zone 4 to zone 1. The results further show that application of high grip and push forces could shift the peak pressure towards zone 3 comprising proximal phalanges of the digits. Under such conditions, the peak pressures are observed to occur over the surface adjoining zones 3 and 4. The results suggest that the peak pressure location is also dependent upon the handle size, particularly under low-magnitude push forces, which may be attributed to the effective contact area. On a relatively large size handle, the subjects tend to apply grip force using the entire hand surface in contact with the handle including the fingertips, which results in relatively higher pressure in zone 4 for the 48 mm handle even when the push force is absent. Subjects tend to maintain a more stable and controlled grip with smaller size handles leading to more concentration of the contact force and thus the peak pressure near the fingertips for the 30 and 40 mm handles. This is further evident from the comparison of magnitudes of mean peak pressures obtained for the two handles. The 30 mm diameter handle yields considerably higher values of mean peak pressures in zone 1 under zero push force.

A few studies have established that the high hand–handle interface pressure, arising from grasping a tool handle, could cause discomfort or pain. High pressure peaks could also impair work performance and lead to potential tissue damage. On the basis of the data derived from algometer studies, the PDT limit of 188 kPa has been estimated for the fingers, while the limits of 200 and 100 kPa have been suggested for the palm and the thenar region, respectively. The corresponding values of the PPT for the finger, palm and thenar were estimated as 560, 576 and 505 kPa, respectively (Johansson et al., 1999). The sustained external applied pressure (SP), considered acceptable for a working day on the average, was estimated as 104 kPa (Fransson-Hall and Kilbom, 1993).

Fig. 4 shows the variations in mean peak pressures as a function of the push force for five levels of constant grip forces and three handle sizes, together with the proposed sustained external pressure (SP) value (Fransson-Hall and Kilbom, 1993). While the results show some nonlinear variations, specifically for high grip force and 30 mm handle, the increasing trend in the peak pressure with increasing push force could be generally approximated as linear. The augmentation of the grip force level tends to shift the mean peak pressure curves upward also in an approximately linear fashion. Fig. 5 illustrates a comparison of the mean peak pressures for the three

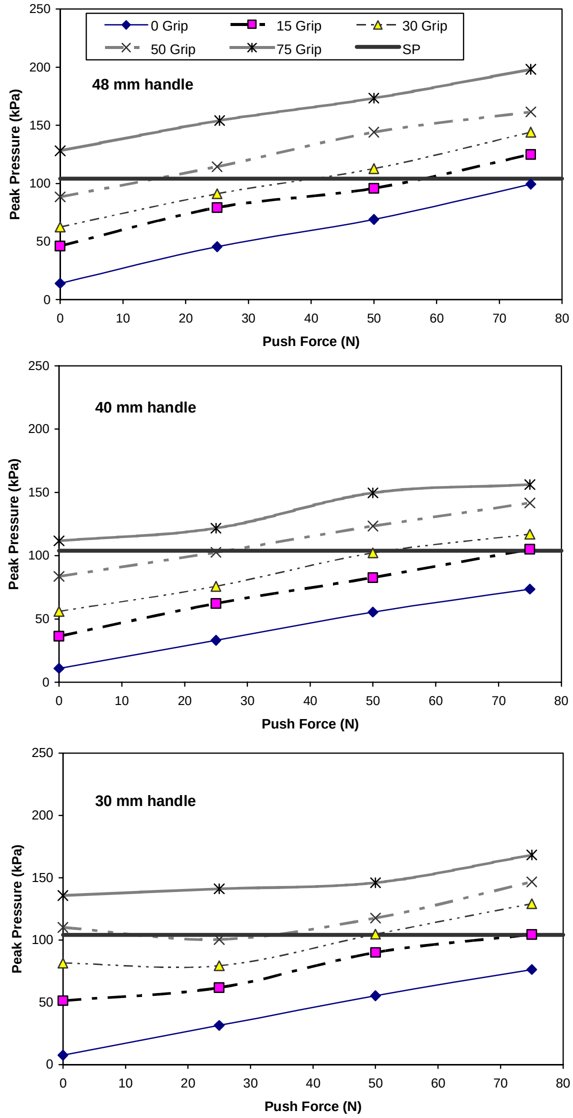

Fig. 4. Variations of mean peak pressure with push force for different constant grip forces and handle sizes.

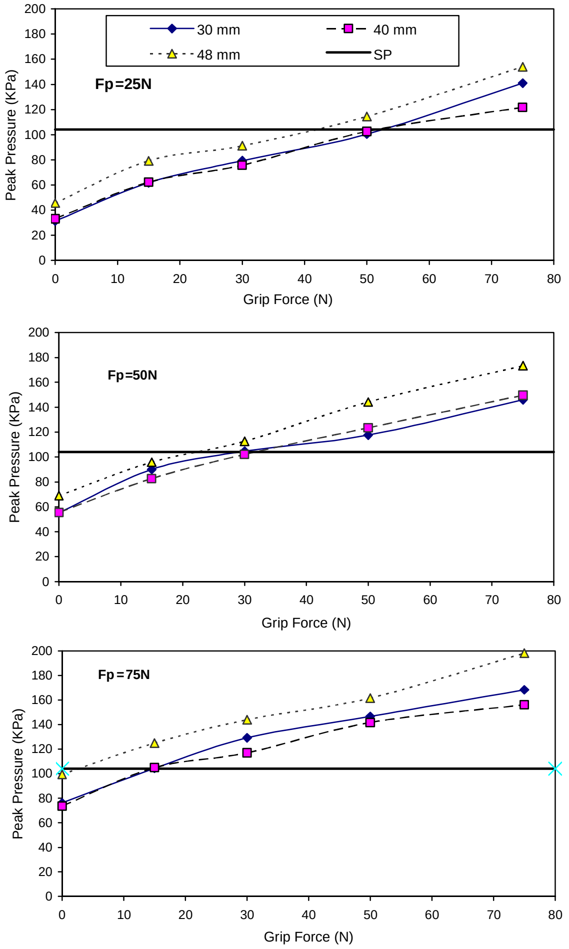

Fig. 5. Hand–handle interface peak pressures as functions of grip and push forces, and handle sizes.

handle sizes and three push force levels (25, 50 and 75 N) as a function of the grip force, together with the SP values. It is obvious from the figure that the 48 mm handle tends to develop the highest peak pressure for all grip/push combinations, while the 30 and 40 mm handles yield similar values of mean peak pressures. The 30 mm handle, however, in general causes higher pressure peaks exceeding SP values under application of higher magnitudes of grip and push forces, when compared to those obtained for the 40 mm handle, which could be attributed to the differences in effective contact areas of the two handles.

4.2. Contact pressure distribution

Figs. 6–8 show variations in the mean peak pressures within the five different contact zones as a function of the push force for three grip force levels and three handles, together with the proposed PDT limit for the thenar (Johansson et al., 1999). For the 48 mm diameter handle, the peak pressures invariably occur within zone 4, irrespective of the magnitudes of the grip and push forces, as shown in Fig. 6. Furthermore, the peak pressures within this zone are considerably higher than those occurring in the other zones. The mean

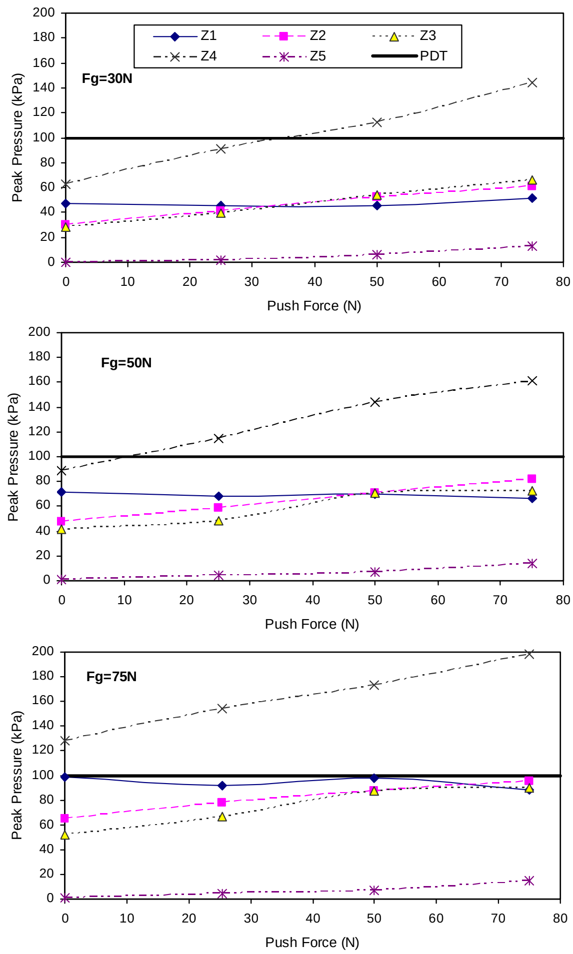

Fig. 6. Peak pressures in different zones as functions of the push and grip forces (48 mm handle; Zone 1—‘Z1’; Zone 2—‘Z2’; Zone 3—‘Z3’; Zone 4—‘Z4’; Zone 5—‘Z5’ and PDT—PDT thenar).

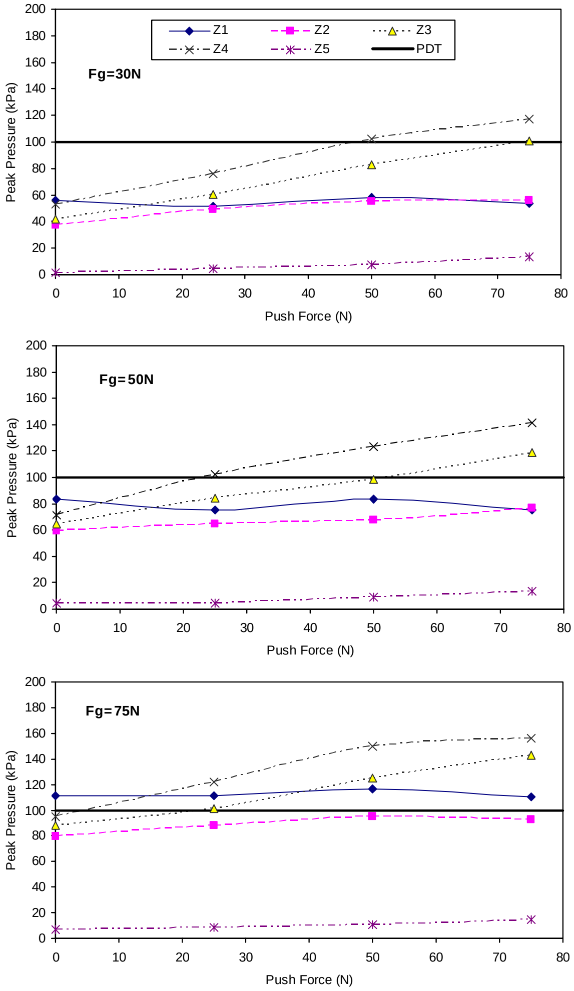

Fig. 7. Peak pressures in different zones as functions of the push and grip forces (40 mm handle; Zone 1—'Z1'; Zone 2—'Z2'; Zone 3—'Z3'; Zone 4—'Z4'; Zone 5—'Z5' and PDT—PDT thenar).

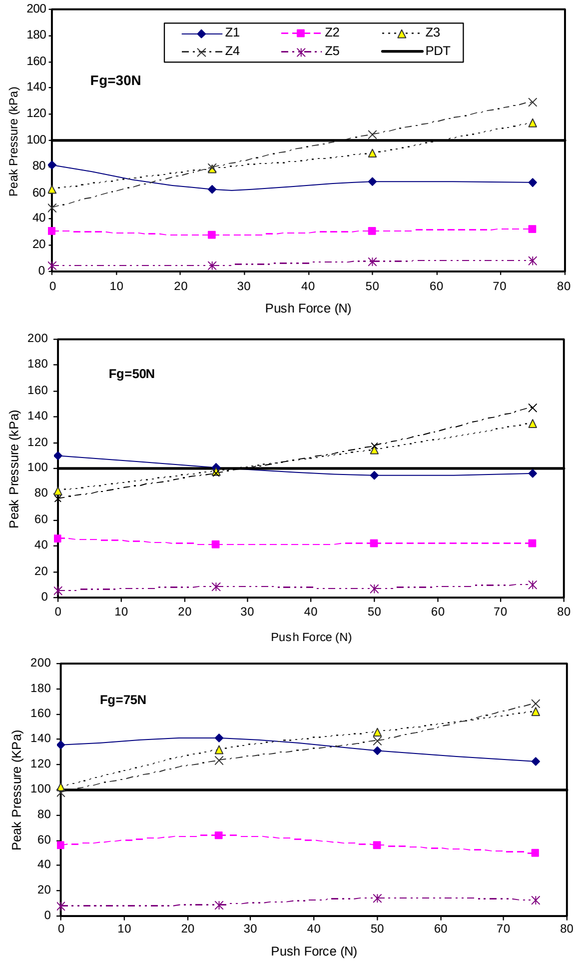

Fig. 8. Peak pressures in different zones as functions of the push and grip forces (30 mm handle; Zone 1—'Z1'; Zone 2—'Z2'; Zone 3—'Z3'; Zone 4—'Z4'; Zone 5—'Z5' and PDT—PDT thenar).

peak pressure in this zone could approach as high as 200 kPa under high magnitudes of hand forces. The peak pressures and thus the contact force developed within zone 4, upper medial side of the palm, are generally observed to be the highest for all three handles, specifically under high push forces. Lower magnitudes of push forces cause relatively higher pressures within zone 1 (the fingertips of second, third and fourth digits), as discussed earlier, which decrease slightly as the push force is increased. The contact force and thus the peak pressure tend to shift from zone 1 to zone 2, comprising the middle phalanges of digits II–IV, as the push force increases further. The results attained for the 40 mm handle also reveal occurrence of peak pressures in zone 4, except under light push force below 25 N, where the peak pressure occurs within zone 1 (Fig. 7). The relative difference in the peak pressures within different zones, however, is considerably smaller when compared to that observed for the 48 mm handle. The results suggest more uniform distribution of peak pressure over zones 1–4 for the 40 mm handle. The shifting of peak contact pressure from zone 4 towards zone 1 becomes more apparent for the 30 mm handle, as shown in Fig. 8. The peak pressures within zones 3 and 4 also approach comparable values, suggesting more uniform distribution of the contact force over the region covering upper medial side of the palm and proximal phalanges of digits III and IV. A comparison of the results presented in Figs. 6–8 suggests that a smaller handle (30 mm) yields higher values of peak pressures in zones 1 and 3, while the larger handle (48 mm) causes high pressures in zone 4. The 30 mm handle thus yields higher contact force than the 48 mm handle.

An examination of the measured pressure data in view of the reported threshold limits suggests that the peak pressures remain well below the PPT values. The measured values, however, exceed the PDT limits suggested for the thenar zone (within zone 4) and the sustained pressure (SP) values with the 48 mm handle under applications of 30 N grip force and push force above 25 N. The application of grip force of 50 N or more coupled with push force above 15 N would generate interface peak pressures above the SP and PDT limits for the thenar area in zone 4, as shown in Fig. 6. Under application of high grip and push forces, such as 75/75 N, the peak pressures exceed the PDT limits for the thenar and approach that for the palm area.

For the 40 mm handle, the peak hand–handle interface pressures exceed SP and PDT limits for the thenar area (zone 4) under application of 30 N grip and push force above 50 N, as evident from Fig. 7. The application of 50 N grip coupled with a 25 N or higher push force would cause peak pressure exceeding PDT of the thenar area. Increasing the grip force to 75 N grip causes higher peak pressures in zone 1 (the fingertips of second, third and fourth digits) and zone 3 (the proximal phalanges of the four digits) that surpass or approach the SP values, irrespective of the push force applied, as shown in Fig. 7. The use of a 30 mm handle with 30 N grip and push force above 50 N could yield peak pressure values well above the PDT limit for the thenar zone (Fig. 8). Application of a 50 N grip force coupled with minimal push force also causes the peak pressure in zone 1 to go above the SP values, while the addition of a 25 N or more push force would cause pressures to exceed PDT limits of the thenar area. Under high grip condition (75 N), the peak pressures developed in zones 1, 3 and 4 exceed the SP limit even in the absence of the push force, as illustrated in Fig. 8. The results suggest that application of high grip and minimal push force on a smaller diameter handle causes high pressures above the SP and PDT limits in zones 1 and 3 (fingertips, and proximal phalanges of the digits). The magnitudes of these pressure peaks are considerably smaller for the large diameter handle, which tends to cause high pressure peaks in the thenar zone.

4.3. Distribution of contact force

The distribution of contact force in the hand/handle interface is further analyzed for different handle sizes and combinations of grip/push forces in terms of contact force ratio (CFR), defined as a ratio of contact force developed within a zone to the total hand–handle contact force. Figs. 9–11 illustrate the CFR for the five zones under different combinations of grip and push forces for the three handles. The results clearly show that zone 4 contributes the most to the total hand–handle interface force for the 48 mm handle, irrespective of the grip and push force combination, as shown in Fig. 9 and also observed from the peak pressure distributions (Fig. 6). The CFR of this zone generally increases with increase in push force, and decreases slightly with increase in the hand grip force. The CFR values in zones 2–4 seem to asymptotically approach steady values with increase in the push force as the effective contact areas saturate. Under the application of a push force alone, the contribution of zone 3 (proximal phalanges of the digits) to the total contact force is highest after zone 4, while the contributions of zone 1 (fingertips) is almost negligible. The steady values of CFR due to zone 1 increase with the increasing grip force. For grip force equal to or higher than 15 N, zones 2 and 3 yield comparable values of CFR, while the contribution due to zone 5 (the medial side of

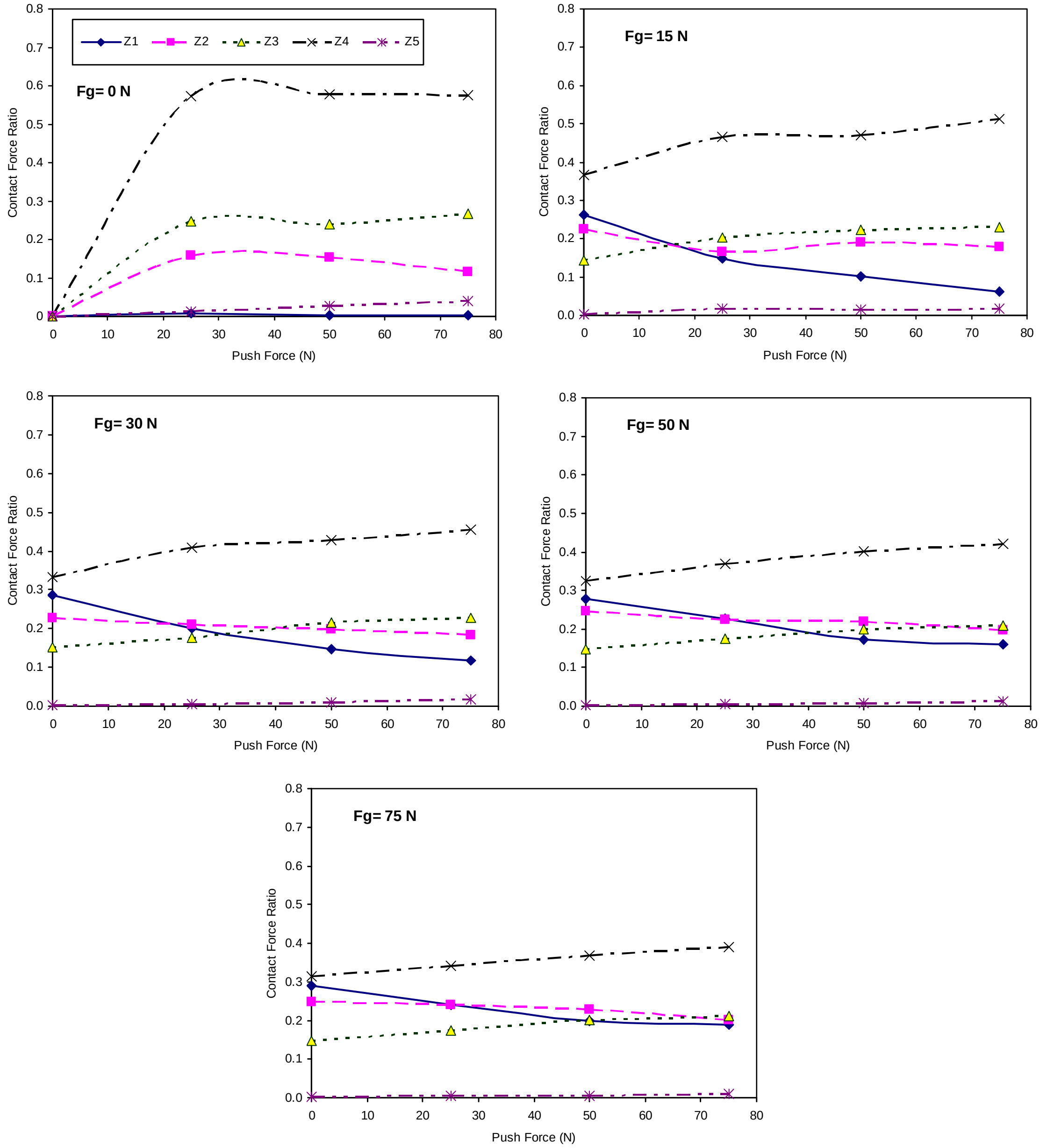

Fig. 9. Contact force distribution among different zones as functions of the push and grip forces (48 mm handle).

the palm) is almost negligible for all grip/push combinations.

The distributions of the contact forces for the 40 and 30 mm handles are quite different from the 48 mm handle, as evident in Figs. 10 and 11, respectively. For the 40 mm handle, the zone 4 yields the highest CFR under either zero or light grip force (15 N); while zone 1 shows the largest CFR under zero push force and all nonzero grip forces. The contribution of zone 3 comprising the proximal phalanges of the digits is higher than that of zone 2. An increase in push force causes an

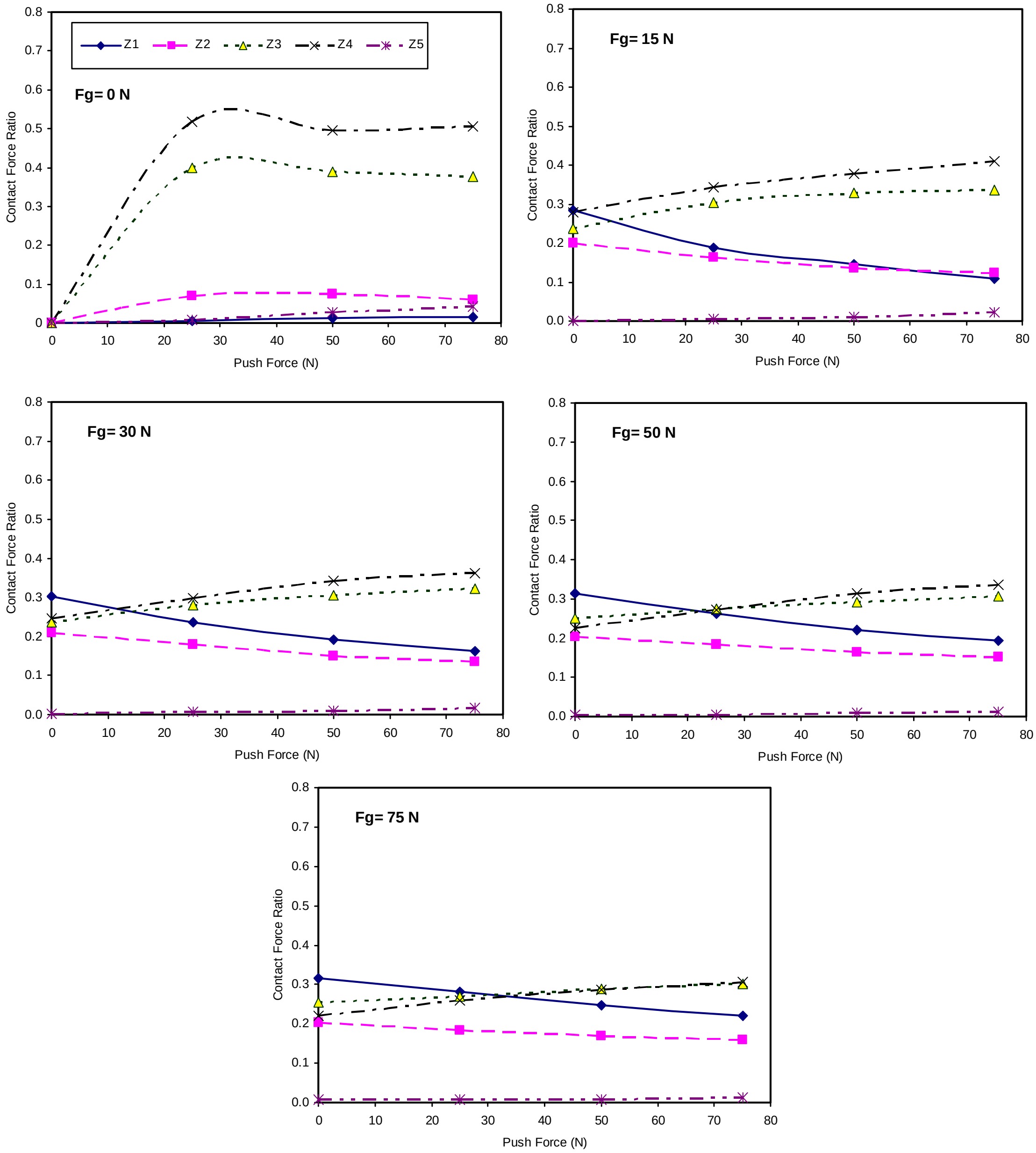

Fig. 10. Contact force distribution among different zones as functions of the push and grip forces (40 mm handle).

increase in CFR of zones 3 and 4, but a decrease in those of zones 1 and 2. For the 30 mm handle, zone 3 tends to contribute the most to the total contact force, specifically when the push force is above 15 N, while zone 1 yields higher CFR for zero push force, suggesting more contact between the fingertips and proximal phalanges, as shown in Fig. 11. The CFR of zone 4 is considerably smaller than those observed for the 40 and 48 mm handles.

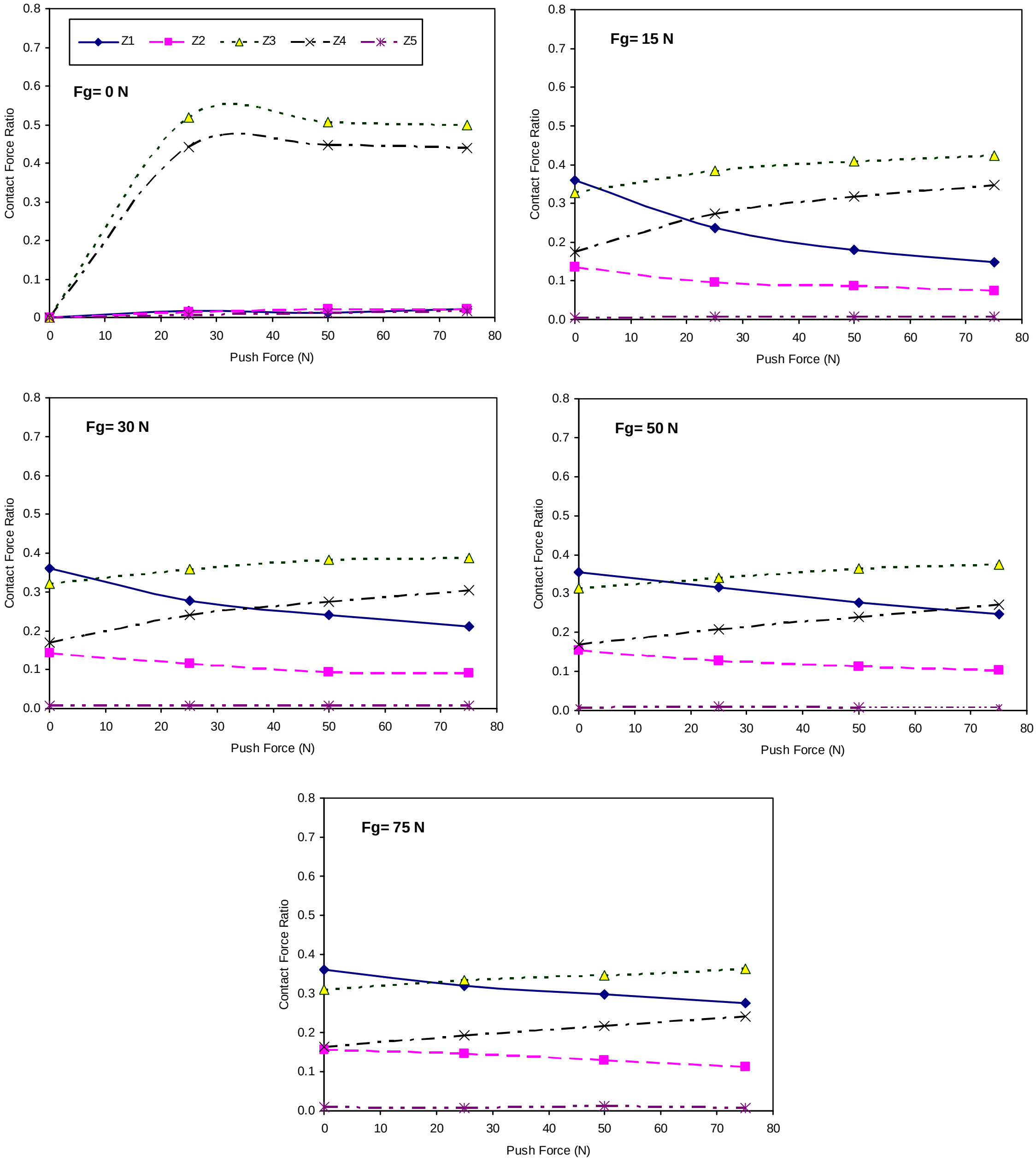

Fig. 11. Contact force distribution among different zones as functions of the push and grip forces (30 mm handle).

Figs. 12–14 demonstrate the CFR of each zone as a function of the push force for different grip forces and handle sizes. The results show similar trends in CFR of different zones for all three handles. The CFR of zone 1 decreases as push force increases, irrespective of the grip force magnitude, and tends to be higher for higher grip force. The CFR of zone 2 comprising the middle

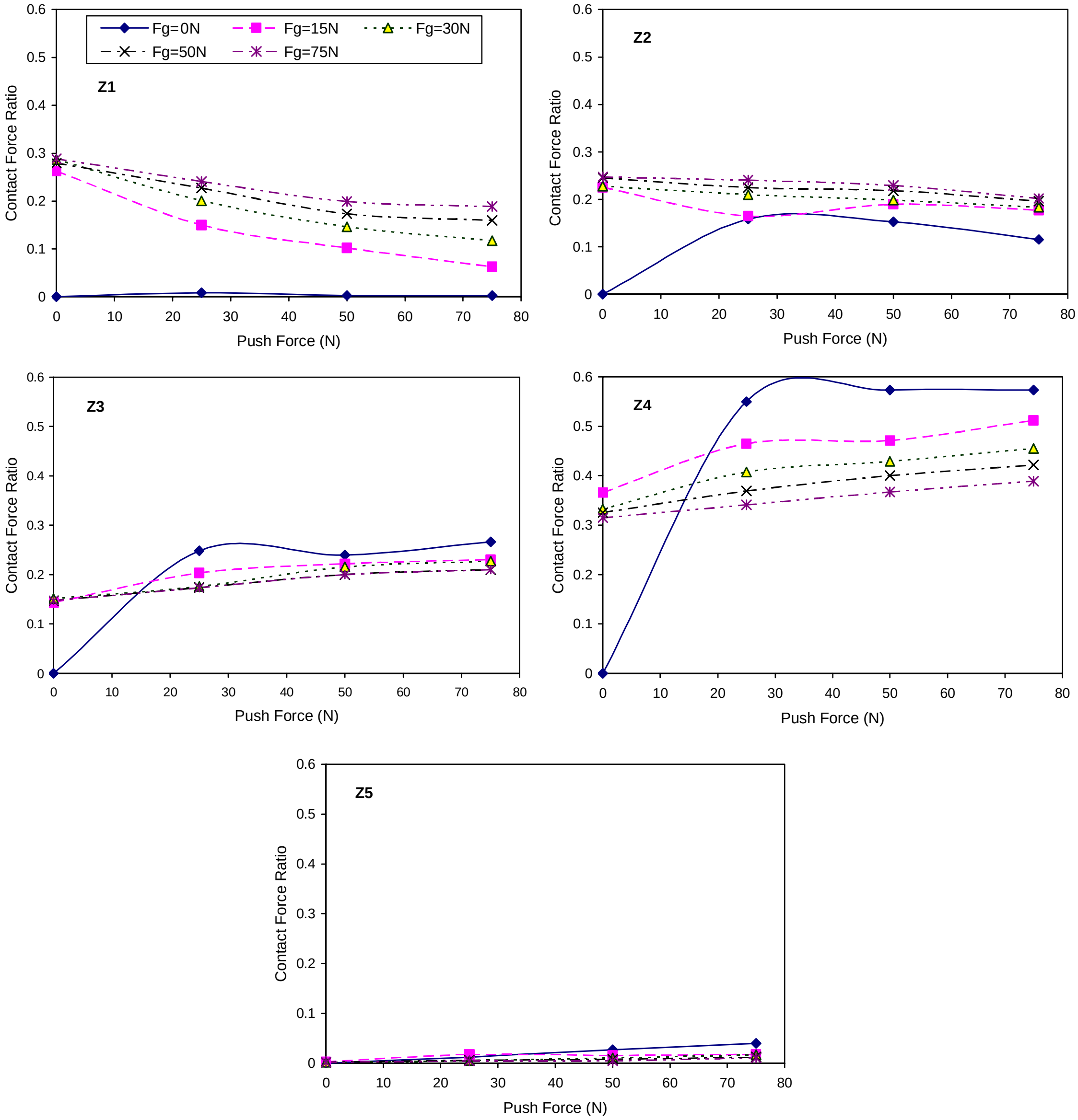

Fig. 12. Contact force contribution in each zone as function of push force for constant grip force for 48 mm handle.

phalanges also exhibits similar trends, while it decays at a relatively slow rate with increase in the push force. The trend, however, differs under zero grip condition, where it initially increases from a zero value to a peak value corresponding to 25 N push force and then either decreases or remains nearly constant. The CFRs of zones 3 and 4 exhibit trends opposite to those observed for zones 1 and 2, where CFRs generally increase with increasing push force and tend to be lower under higher grip applied by the subjects. The CFR in zone 4 increases considerably with the increase of push force and decreases with higher levels of grip force. The CFR of zone 5 comprising upper medial

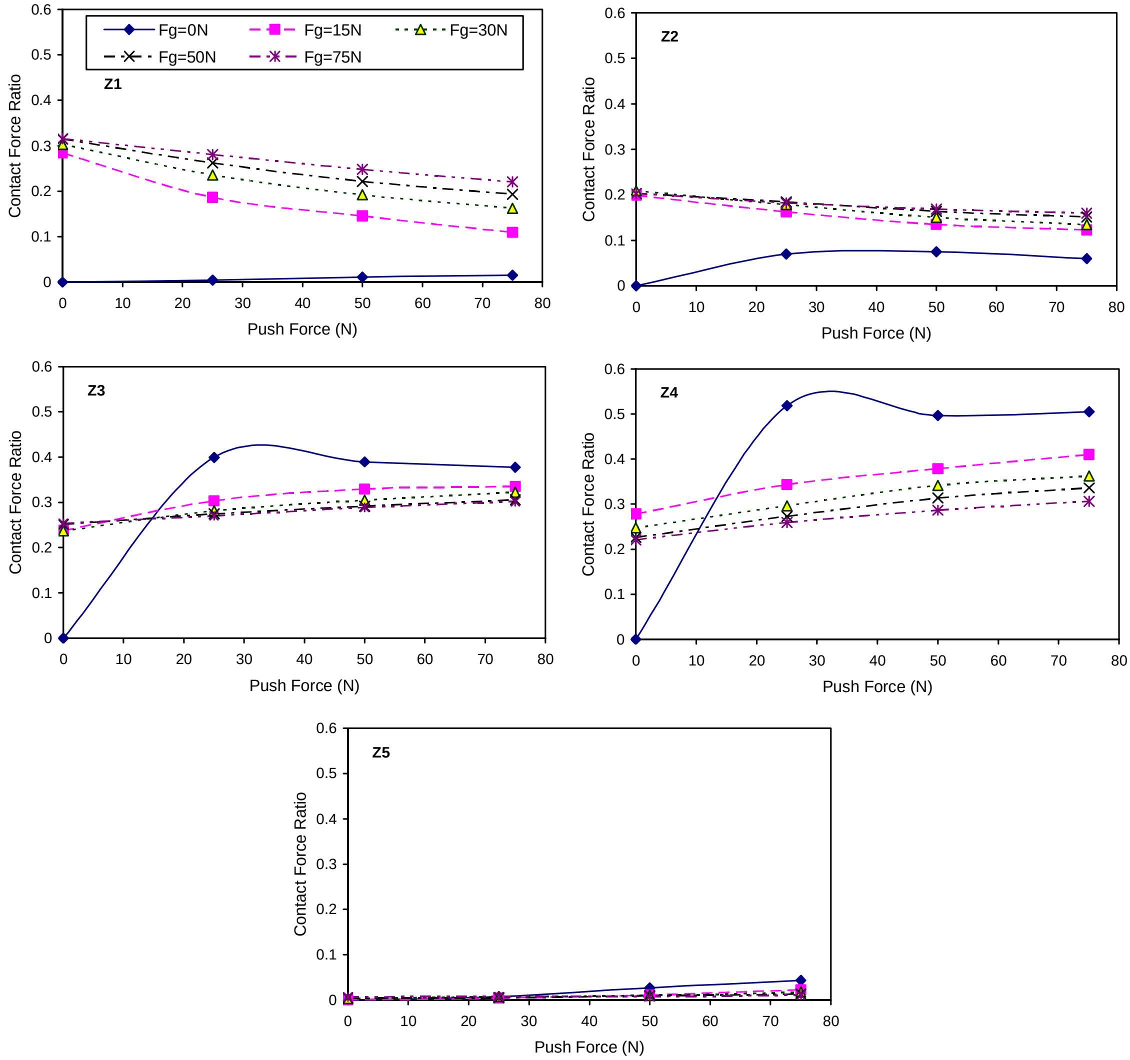

Fig. 13. Contact force contribution in each zone as function of push force for constant grip force for 40 mm handle.

side of palm is negligible for almost all levels of grip/push forces and handle sizes.

4.4. Relationship between peak pressure (PP) and hand forces

Multi-factor ANOVA analyses within subject effect have been carried out using SPSS to verify the statistical significance of handle size, push and grip forces on the hand–handle interface peak pressure. The one-way analysis revealed that the grip and push forces have obvious statistical significance on the interface hand–handle peak pressure ($p<0.001$), while the handle size is fairly significant ($p<0.05$). The results presented in Figs. 4 and 5 further suggest that the peak pressure is dependent upon not only the grip and push forces, but also on the handle diameter. Two-way ANOVA analyses revealed significant interactions between handle size and grip force, and between the grip and push forces, while no interaction was found between the handle size and the push force.

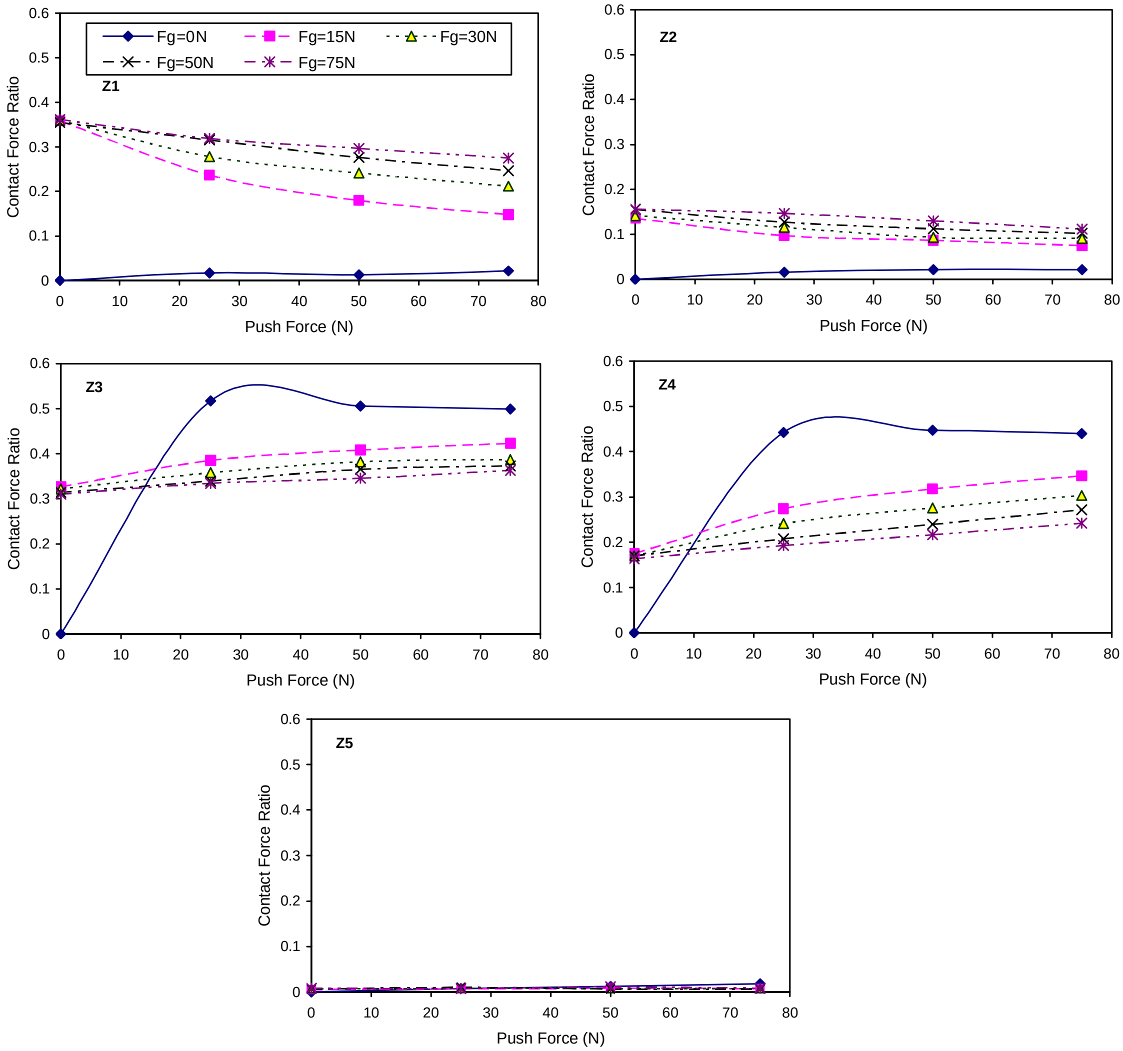

Fig. 14. Contact force contribution in each zone as function of push force for constant grip force for 30 mm handle.

The dependence of PP on the F_g and F_p alone may thus be described by a linear function of the form

$$PP = K(D) + A(D)F_g + B(D)F_p, \quad (2)$$

where $K(D)$, $A(D)$ and $B(D)$ are coefficients dependent on the handle diameter. The constant $K(D)$ is introduced to account for variations in peak pressures imposed by the subjects under 0 grip and 0 push force conditions, and offset in the peak pressure possibly caused by a residual pressure in the sensing mat wrapped around the handle. Coefficients $A(D)$ and $B(D)$ describe the relative contributions due to grip and push forces to the peak pressure, respectively. Multiple linear regressions were performed to identify the coeffi-

Table 3
Model coefficients characterizing peak pressure dependence on the grip and push forces

Handle diameter	$K(D)$	$A(D)$	$B(D)$
30 mm	32.4	1.28	0.593
40 mm	20.1	1.16	0.809
48 mm	24.9	1.34	0.996

cients for each handle, and the resulting handle-size-dependent coefficients are summarized in Table 3. The correlation coefficients (r^{2m}) of these linear regressions were obtained as 0.942, 0.977 and 0.99, respectively, for 30, 40 and 48 mm handles. A good correlation is obtained between the estimated and measured mean values of peak pressures, as evident in Fig. 15.

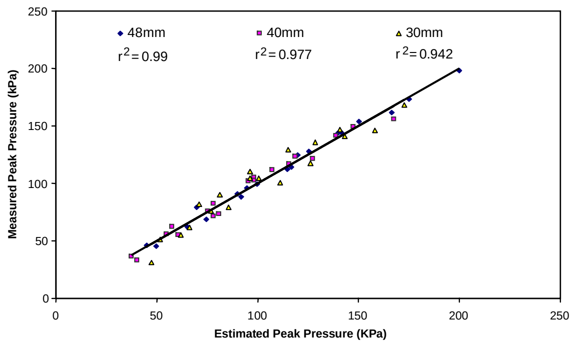

Fig. 15. Correlation between measured and estimated mean peak pressure for three different handles.

The coefficient values reveal that the contribution of the grip forces to the peak pressure value is far more significant than that of the push force, which has also been observed for the total contact force (Welcome et al., 2001). Fig. 16 illustrates the variations in the regression coefficients with the handle size. The push force coefficient, $B(D)$, varies approximately linearly with the handle size in the range considered in this study, and thus may be expressed as ($r^2 > 0.95$)

$$B(D) = -0.080 + 0.0224D, \tag{3}$$

where D is the handle diameter in mm. The grip force dependent and constant coefficients, however, show nonlinear variations with the handle diameter, and both the coefficient values are observed to be smaller for the 40 mm handle. The dependence of both coefficients upon the diameter could be best described by a quadratic

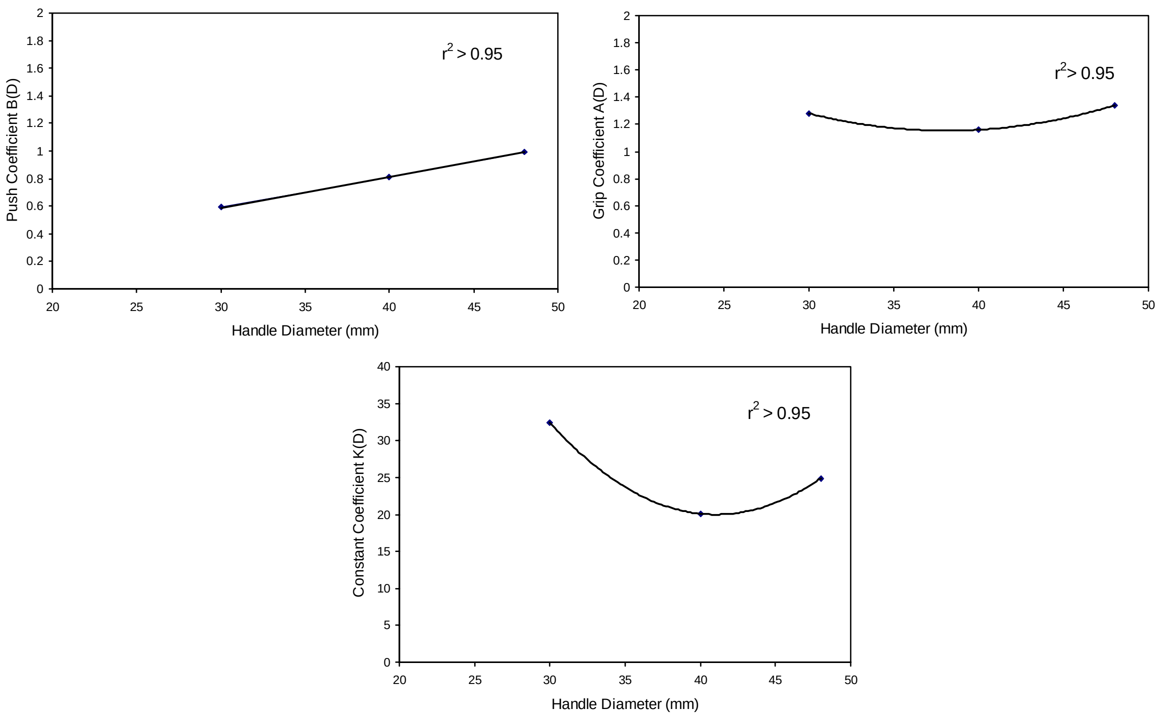

Fig. 16. Relationships between handle diameter and grip, push and constant coefficients in peak pressure equation.

function of the form ($r^2 > 0.95$)

$$A(D) = 0.0019D^2 - 0.1462D + 3.94, \quad (4)$$

$$K(D) = 0.102D^2 - 8.3467D + 191.3. \quad (5)$$

The coefficient $K(D)$ may be considered as a bias in the measurement, attributed to few hot pressure points that are observed under zero grip and push condition, when the hand is merely placed on the handle.

4.5. Relationship between the zonal contact force and hand forces

The results, presented in Figs. 9–11, show that the distribution of contact force in the hand–handle interface strongly depends on the grip and push forces, and the handle diameter. Multiple linear regression analysis showed linear variations in the contact forces measured in each zone with grip and push forces for all handles, while the correlation coefficients obtained were higher than 0.99 in all cases. Owing to the extremely small contact force in zone 5, the data attained for zone 5 was added to zone 4. The resulting zone, referred to as zones 45, would thus represent the upper palmar surface of the hand. The contact force developed within each zone can thus be expressed as a linear combination of the grip and push forces, in the following manner:

$$CF_j = \alpha_j(D)F_g + \beta_j(D)F_p; \quad j = 1, 2, 3, 45, \quad (6)$$

Table 4
Grip (α_j) and push force (β_j) dependent coefficients describing their contribution to the contact force developed in different zones

Handle diameter	α_j	β_j	α_j	β_j
	ZONE 1		ZONE 2	
30	1.270	0.039	0.541	0.019
40	0.910	0.024	0.585	0.096
48	0.704	0.000	0.626	0.170
	ZONE 3		*ZONE 45*	
30	1.12	0.602	0.623	0.567
40	0.745	0.482	0.672	0.658
48	0.405	0.347	0.785	0.757

where CF_j is the contact force developed within zone j, and α_j and β_j are the grip and push force coefficients, which depend upon the handle size.

Table 4 summarizes the coefficient values for different zones and handle sizes considered. The results show that the contact force developed in zones 3 and 45, comprising proximal phalanges of the digits and the upper palmar surface, is generally more attributed to the grip and push force, while that in zones 1 and 2 it is mostly caused by the gripping action. The small size handle (30 mm) yields higher contact forces attributed to the handle grip at the fingers surface (zones 1,2 and 3), while the handle grip contributes more to the forces developed in zones 1 and 2 in case of the 48 mm handle. The variations in the grip-dependent coefficient α_j for the three zones ($j = 1$, 2, 3) are observed to be the highest for the 30 mm handle and least for the 40 mm handle. The contact force developed in zones 45, and attributed to the gripping action, shows less sensitivity to the handle diameter. The contact force developed in this zone shows somewhat comparable contributions due to grip and push forces for all three handle sizes.

5. Conclusion

The magnitudes and distribution of hand–handle interface pressure during a gripping and pushing task vary considerably with the applied grip and push forces, and the handle diameter. The peak pressure for a given handle size could be estimated from a linear combination of the directly measurable grip and push forces, where the weighting of the grip force is considerably higher than the push force. The large size handle (48 mm diameter) yields the highest magnitude of interface peak pressure, while the small handle (30 mm diameter) causes higher contact force, suggesting more uniform pressure distribution over smaller size handles. The locations of localized pressure peaks in the operator's hand vary considerably with handle size and applied grip/push forces. The large size handle considered in this study causes the pressure peaks to occur in the lateral side of the palm (zone 4) for the entire range of grip and push forces considered. Furthermore, the pressure peaks within this zone are considerably higher than those occurring in the other zones, and exceed the reported threshold limit of the pressure discomfort (PDT) and sustained pressure (SP) values for preservation of working efficiency over a work day.

Gripping a 40 mm handle in the absence of push force tends to shift the pressure peaks to the fingertips (zone 1). For a 30 mm handle, the pressure peaks also tend to spread to the proximal phalanges of the digits (zone 3) depending on the applied grip and push forces. The relative differences in peak pressures within different zones for the 30 and 40 mm handles are considerably smaller than those observed for the 48 mm handle, suggesting more uniform distribution of pressure for smaller handles. From the results it is concluded that gripping a relatively large size handle encourages the subjects to apply grip force over the entire hand surface in contact with the handle including the fingertips, which results in relatively higher pressure in the lateral side of the palm even when the push force is absent. Subjects tend to maintain a more stable and controlled grip with the smaller size handles (30 and 40 mm) considered in the study, leading to relatively higher contact force and thus the peak pressure near fingertips.

The application of high grip and push forces, such as 75/75 N, on a 48 mm handle causes peak pressures to exceed the PDT limit for the thenar and approach that for the palm area. For the 30 and 40 mm handles, the peak interface pressures exceed SP and PDT limits for the thenar area under application of 30 N grip and push force above 50 N. Increasing the grip force beyond 50 N causes higher peak pressures in zones 1 and 3 (fingertips and proximal phalanges of the four digits) that surpass or approach the SP values, irrespective of the push force applied. The results suggest that application of high grip and minimal push force on a smaller diameter handle causes high pressures above the SP and PDT limits in zones 1 and 3. The magnitudes of these pressure peaks are considerably smaller for the large diameter handle, which tends to cause high pressure peaks in the thenar zone. The results suggest that further efforts would be desirable to identify alternate handle sizes and geometry in order to distribute the contact pressure more evenly and to limit the pressure peaks below acceptable PDT and SP values.

The CFR, defined as a ratio of the contact force developed within a zone to the total contact force could also be estimated from a linear combination of the grip and push forces. The relative contributions of grip and push forces to the CFR for different zones differ considerably. The results show that the contact force developed at the hand–handle interface of the large size handle is mostly attributed to the force developed in zone 4 (lateral side of palm), irrespective of the magnitudes of grip and push forces applied. The CFR of this zone generally increases with increase in push force and decreases only slightly with increase in the hand grip force. A 40 mm handle also yields highest CFR due to zone 4 only under zero or light grip condition, while the fingertips zone exhibits highest CFR under zero push and all nonzero grip forces. The distribution of the contact forces for a smaller (30 mm) handle is observed to be quite different. The contact force developed within zone 3 (proximal phalanges of digits) contribute most to the total contact force, specifically when the push force is above 15 N, while the CFR of zone 1 tends to be higher for zero push force, suggesting more contact between the fingertips and proximal phalanges.

It has been suggested that the severity of the risk posed by exposure to hand-tools vibration is strongly related to contact force. The biodynamic response of the hand and arm exposed to vibration under finger grip condition differs considerably from that under palm grip condition. A quantitative estimate of the total and localized contact forces may thus be essential for study of biodynamic response of the hand–arm system to vibration rather than applied grip or push forces.

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