



Development of a new dynamometer for measuring grip strength applied on a cylindrical handle^{*}

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ABSTRACT

The objective of this study is to enhance the understanding of the hand grip force applied to a cylindrical handle and to develop a new dynamometer for measuring maximum grip force or grip strength. Specifically, a 40 mm instrumented cylindrical handle with six measuring arms was developed. A theoretical model was proposed and used to analyze the principle of the measurement. Human test subjects were used in conducting two sets of experiments to evaluate the handle and to assess the measurement method. This study confirmed that some friction force exists in the grip-only action, but its level is not comparable with the normal force. This study also found that the friction force can stabilize the grip action and marginally increase the grip strength. No reliable correlation between the grip strengths measured with the 40 mm cylindrical handle and Jamar handle with a 47.6 mm span was observed. This suggests that grip strength measured with Jamar handle may not be reliably applicable to the design and risk assessment of some tools or machines with cylindrical handles. In contrast, the cylindrical handle proved to be able to determine the overall grip strength for a subject, as well as show the grip force distribution around the circumference of the handle. The handle is accurate with less than 4% error, and it demonstrates that the measurement is independent of the loading position along the handle. Therefore, this study concluded that this new dynamometer is suitable for measuring grip strength with sufficient precision.

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1. Introduction

Repeated forceful hand exertion is associated with a series of musculoskeletal disorders (MSDs) such as hand tendonitis, strained muscles, and carpal tunnel syndrome [1,2]. It is also one of the important factors that can influence the development of hand-arm vibration syndrome [3]. The hand force applied can be quantified as a percent of the maximal grip force or grip strength resulting from the maximum voluntary contraction of muscles. An assessment of grip force and/or grip strength is required for most tool and task designs and for risk evaluation of these MSDs [4–8]. Grip strength can also be used to help diagnose these MSDs, to examine effectiveness of their treatments, and to evaluate the functional capacity of workers [9,10]. The handgrip strength is also frequently measured as a total fitness parameter of the population or in sport practices [11]. Although many studies on this subject have

been reported, the measurement of grip force and grip strength applied to cylindrical handles remains an issue for further studies.

The Jamar dynamometer, as well as modified Jamar versions, have been used for the measurement of grip strength [2,12], but the measured grip strength may not be well representative of all muscle actions or grip efforts applied on a cylindrical handle. Several devices comprising cylindrical handles equipped with force sensors or strain gauges have also been used to measure grip strength [13,14]. However, they can only be used to measure the grip strength in one direction at a time [14]; more comprehensive characterizations of grip efforts applied to cylindrical handles requires measuring grip strength in more than one direction [15]. To avoid the difficulties in measuring grip strength in various orientations, Welcome and his colleagues proposed to quantify the grip effort by measuring the total grip contact force perpendicular to the handle surface [14]. Such measurements can be achieved by wrapping a matrix of flexible contact pressure sensors on the handle [14,16]. A major concern with this approach is that the currently available flexible pressure sensors require a certain level of expertise to achieve a reliable measurement as the sensors are delicate. The measured pressure may also vary with time, temperature, contact surface texture and curvature, thus adding further technical complications. It is also difficult to accurately calibrate the

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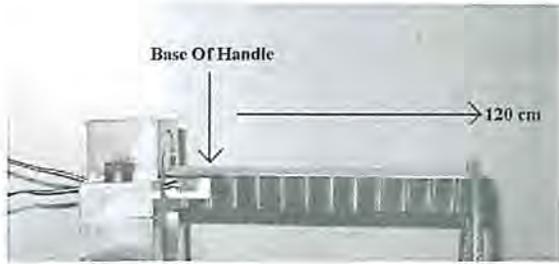


Fig. 3. Measuring arm calibration test setup.

2.2. Handle calibration

As shown in Fig. 3, each arm was fixed on the base individually and then mounted in a holding device and clamped to the end of a table. Dead weights were suspended by a cable on each arm at seven different locations along the length of the arm. Five weights (11.3, 31.3, 63.1, 168.5, and 333.6 N) were used. In the calibration, a regression equation was used to represent the relationship between the applied force and the measured force. The resulting calibration factors were incorporated into the above-mentioned LabVIEW program so that the actual grip force was directly displayed and recorded.

2.3. Theoretical analysis

To help understand the multi-arm measurement method, a model of the grip force was proposed, as shown in Fig. 4. Normal and tangential pressures generally exist at the hand-handle interface in a grip exertion [18]. Theoretically, the distributed pressures (p_N and p_T) can be summed to determine the pressures per unit length around the handle circumference in a plane perpendicular to the longitudinal axis of the handle, as shown in Fig. 4(a). The equivalent force of the pressures on each measuring arm can be

expressed as the following three components: normal force (N), tangential force (T), and moment (M) acting at the center of each arm, as shown in Fig. 4(b). Only the normal force is measured with the multi-arm handle. A critical question is whether the measured normal force is sufficient for representing the total contact force.

With the model shown in Fig. 4(c), the formula for computing each normal force shown in Fig. 4(b) was derived, which is expressed as follows:

$$N_i = \int_{-\pi/n}^{\pi/n} p_N(\alpha_i + \theta) \cdot \cos(\theta) \cdot R \cdot d\theta + \int_{-\pi/n}^{\pi/n} p_T(\alpha_i + \theta) \cdot \sin(\theta) \cdot R \cdot d\theta \quad (1)$$

where α_i is the global angle of the i th arm, n is the number of arms of the handle, θ is the local angle in the angular range ($2\pi/n$) of each arm, and R is the radius of the handle.

This equation indicates that the normal force is composed of two components: the component resulting from the normal contact pressure, which is expressed in the first term of Eq. (1), and the component resulting from the tangential contact pressure, which is expressed in the second term of Eq. (1). As dictated by the first term of Eq. (1), the normal pressure on each measuring arm is projected to the radial direction at the middle of the arm, and the resulting force components are summed to form the first part of the normal force (N) actually measured by the arm sensor. Because of the projection process, this part must be less than the total normal contact force acting on the arm. The measured percentage is theoretically a function of the number of arms used in the handle structure and the normal pressure distribution. To obtain an approximate estimate of the percentage, the normal pressure is assumed to be uniformly distributed around the handle. With this assumption, the percent force (λ_n) measured with an n -arm handle can be derived from the

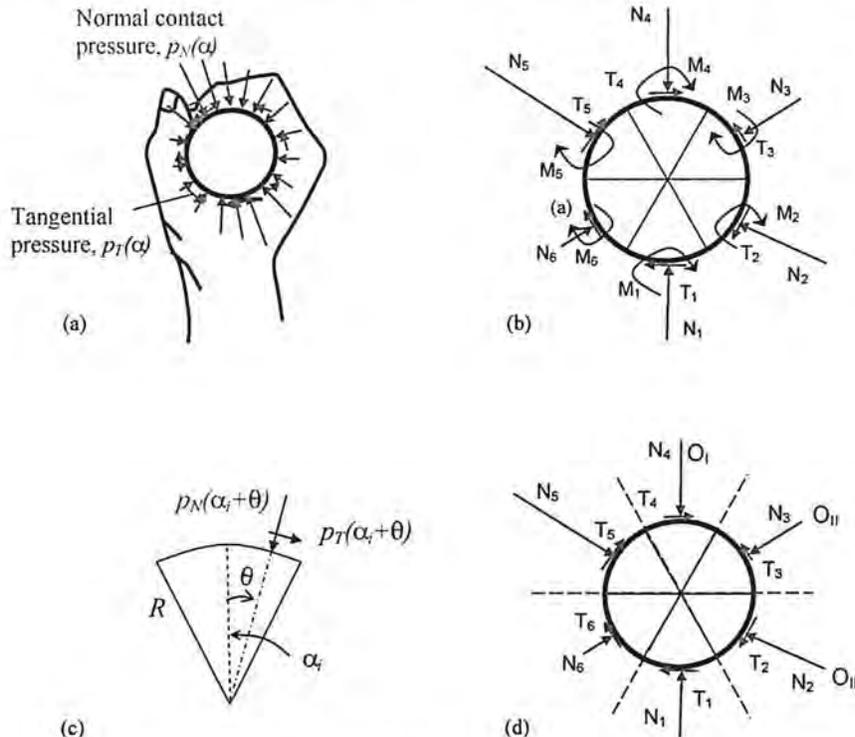


Fig. 4. A theoretical model of grip strength: (a) distributed normal and tangential pressures; (b) equivalent forces on each measuring arm; (c) calculation of the equivalent forces on each measuring arm; and (d) Orientations (O_I = Orientation 1, O_{II} = Orientation 2, and O_{III} = Orientation 3) for measurement of percent differences for 6 arm handle.

following equation:

$$\lambda_n = \frac{n \int_{-\pi/n}^{\pi/n} p_N \cdot \cos(\theta) \cdot R \cdot d\theta}{\int_0^{2\pi} p_N \cdot R \cdot d\theta} = \frac{n \cdot \sin(\pi/n)}{\pi} \quad (2)$$

In such a case, only 63.7% of the normal contact force is measured with the conventional two-arm cylindrical handle [14], but the percentage reaches 95.5% with the six-arm handle. Further increasing the number of arms only slightly increases the percent force measured (e.g., 97.4% for an eight-arm handle and 98.4% for a ten-arm handle).

If the enclosed angle of each arm ($2\pi/n$) is sufficiently small, the second component, or the contribution of the tangential pressure to the normal force, can be ignored. However, this is not the case of this study, because the enclosed angle is equal to 60° for the six-arm handle, 45° for the eight-arm handle, and 36° for the ten-arm handle. In the grip-only exertion, the tangential pressure results primarily from the friction between the hand and handle. Theoretically, the relationship between the tangential pressure and the normal pressure is as follows:

$$|p_T| \leq \mu \cdot p_N \quad (3)$$

where μ is the coefficient of friction. According to the torque and grip force measured on cylindrical handles under several surface conditions reported in [20], the estimated μ -value is greater than 0.32. A much higher hand μ -value is reported in [21]. However, the friction force is usually far from fully developed in the grip-only exertion, as evidenced from the fact that the reported friction force in such an exertion is much less than the normal force [18]. Furthermore, the tangential pressure could be positive in one part of the arm span and negative in the other part, depending on the handle size and the contact location [18], which may partially cancel the tangential pressure contribution. These observations suggest that the friction force can be partially reflected in the normal force measurement, but is not likely to be substantial.

Similar to the normal force, the tangential force shown in the model in Fig. 4 can be calculated from:

$$T_i = \int_{-\pi/n}^{\pi/n} p_N(\alpha_i + \theta) \cdot \sin(\theta) \cdot R \cdot d\theta + \int_{-\pi/n}^{\pi/n} p_T(\alpha_i + \theta) \cdot \cos(\theta) \cdot R \cdot d\theta \quad (4)$$

The first term of the equation indicates that the normal pressure-induced tangential force results from the asymmetric distribution of the normal pressure on the curved surface of each arm. Because the normal pressure is usually asymmetrically distributed, the total tangential force generally exists in a grip action even if the friction force is completely ignored. In essence, an imbalance of normal forces will result in a tangential component, not to be confused with a tangential force created by friction (shear) force.

Similar to the normal pressure's larger contribution to the normal force on each arm of the handles shown in Fig. 1, the tangential pressure has a larger contribution to the tangential force than does the normal pressure, because of the difference between their weightings ($\cos(\theta)$ vs. $\sin(\theta)$) in Eq. (4). Such a difference also increases with the increase in the number of measuring arms. Therefore, if the asymmetry of the normal pressure can be ignored or the first term in Eq. (4) is small, the tangential force mainly results from the tangential pressure or friction force.

In principle, if the dynamic force can be ignored, all of the forces acting on the handle shown in Fig. 4(b) must be balanced in any given direction or orientation. Furthermore, if the tangential force can be ignored, the normal force acting on any half of the handle

is the same as that on the other half of the handle. Therefore, a series of equations was developed to examine whether or not the tangential force plays a major role in the overall grip strength. Each equation represents an orientation in which the normal forces were summed into two different halves. The percent differences between the forces on two halves in the three possible orientations of the six-arm handle were calculated from:

for Orientation I

$$O_I = \frac{((N_5/2) + N_4 + (N_3/2)) - ((N_2/2) + N_1 + (N_6/2))}{((N_5/2) + N_4 + (N_3/2) + (N_2/2) + N_1 + (N_6/2))/2} \times 100\% \quad (5)$$

for Orientation II

$$O_{II} = \frac{((N_4/2) + N_3 + (N_2/2)) - ((N_1/2) + N_6 + (N_5/2))}{((N_4/2) + N_3 + (N_2/2) + (N_1/2) + N_6 + (N_5/2))/2} \times 100\% \quad (6)$$

for Orientation III

$$O_{III} = \frac{((N_3/2) + N_2 + (N_1/2)) - ((N_6/2) + N_5 + (N_4/2))}{((N_3/2) + N_2 + (N_1/2) + (N_6/2) + N_5 + (N_4/2))/2} \times 100\% \quad (7)$$

where N_i represents the normal force measured by the n th arm. The three orientations for the six-arm handle are depicted in Fig. 4(d). Theoretically, the better the normal forces are balanced, the less of a role the tangential force plays in the overall grip strength. Because the tangential force mainly results from the friction force, these equations can also be used to examine the influence of the friction force on the grip force or grip strength.

2.4. Experiments

The protocol for this research was reviewed and approved by the NIOSH Human Subjects Review Board. Pilot tests demonstrated that the grip strength measured with the six-arm handle was practically independent of longitudinal hand placement. However, the eight- and ten-arm handle measurements varied with the grip location. Therefore, only the six-arm handle was used in the experiments to examine the behaviors of this handle and the measurement method.

As shown in Fig. 5(a), the handle was suspended from an overhead fixture by a string so that no torque, pushing, or pulling forces could be applied to the handle during the experiment. The handle height was adjusted for each subject such that he/she could apply his/her grip exertion on the handle with the wrist at its neutral position in a natural standing body posture without changing the handle vertical orientation, as shown in Fig. 5(b). To standardize trial-to-trial hand direction, markers were placed at the middle of Arm 1, on the thenar region of the subject's hand, and on the top of the forearm near the elbow; at the start of each trial, the subject aligned the marker on the front side of the handle with the marker on the thenar region of the hand before applying the grip effort, as shown in Fig. 5(a–c). The alignment of the other marker near the elbow was used as a visual alignment tool to check for correct posture while gripping.

Two series of experiments were conducted. Six subjects participated in the first experiment to explore the friction effect. Table 1 lists several hand anthropometry parameters and the means and standard deviations (SD) for the six subjects. To evaluate different friction conditions, this study considered three hand-handle treatments: (i) bare hand on a clean machined aluminum handle; (ii) hand with a medical latex glove on a clean handle; and (iii) hand with a medical latex glove on an oiled handle. To protect the handle during the oiled handle treatments, a thin layer of plastic cling wrap was loosely wrapped around the handle and fixed at the top with adhesive tape. Caution was taken so that no additional forces

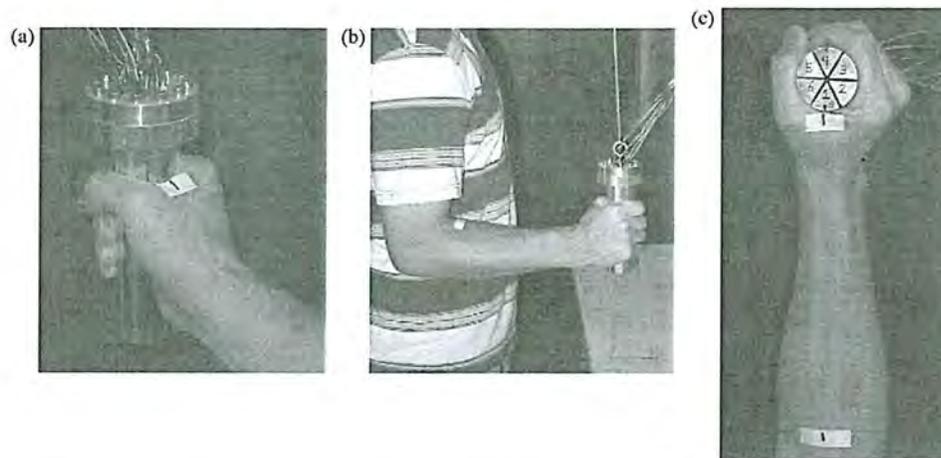


Fig. 5. Hand and arm postures in the experiments: (a) hand grip posture and hand-handle alignment marks; (b) side view of arm posture; and (c) vertical view of arm posture and the relationship between measuring arms and the hand grip orientation.

Table 1

Anthropometry of the subjects participating in the first experiment (hand length = tip of middle finger to crease at the underside of the wrist; hand breadth = the width measured at the metacarpophalangeal joint line; hand circumference = the circumference measured at the metacarpophalangeal joint line of the open hand).

| Subject | Gender (m/f) | Stature/height (cm) | Weight (kg) | Hand length (mm) | Hand breadth (mm) | Hand circumference (mm) |
|---------|--------------|---------------------|-------------|------------------|-------------------|-------------------------|
| 1 | m | 182.9 | 88.4 | 192 | 89 | 215 |
| 2 | m | 182.9 | 97.5 | 196 | 91 | 220 |
| 3 | m | 177.8 | 77.2 | 193 | 83 | 206 |
| 4 | m | 175.3 | 70.7 | 188 | 88 | 210 |
| 5 | m | 162.0 | 62.6 | 184 | 78 | 186 |
| 6 | f | 160.0 | 55.0 | 164 | 75 | 182 |
| Mean | | 173.5 | 75.2 | 186 | 84 | 203 |
| SD | | 10.1 | 15.9 | 12 | 7 | 16 |

were generated on the arms due to the cling wrap. Both the plastic wrap and the gloved hand were coated with mineral oil for this treatment.

Each subject was advised to apply his/her maximum grip with the right hand for 5 s. Data collection began once the subject nodded to acknowledge he/she was applying a full grip action. The sampling rate was 5 Hz. Only the middle 3 s in each data collection period were used to determine the average value of the maximum grip effort. The subjects rested for 3 min between trials. The three experimental treatments were randomized for each subject. Three trials were sequentially performed in each test treatment.

To verify that the coefficient of friction in the oiled hand treatment is substantially less than those in the other two hand treatments, a μ -value measurement was performed with two sub-

jects using a purpose-built skin friction meter constructed in house. The normal and friction forces acting at the interface between the palm of an open hand and a smooth flat aluminum plate were simultaneously measured, and the data were used to evaluate the μ -value for each of the three hand treatments.

To further evaluate the behaviors of the dynamometer and to explore the relationship between the grip strength measured with the cylindrical handle and a Jamar handle, ten subjects participated in the second experiment using the same experimental setups and body postures used in the first experiment. Their anthropometry parameters are listed in Table 2. The Jamar handle was set to the second shortest span (47.6 mm at the midpoint of the gripping surface), which is the setting closest to simulating the 40 mm cylindrical handle. Only the bare hand on a clean, dry handle scenario was considered in this experiment. The grip posture on the Jamar han-

Table 2

Anthropometry of the subjects participating in the second experiment (hand length = tip of middle finger to crease at the underside of the wrist; hand breadth = the width measured at the metacarpophalangeal joint line; hand circumference = the circumference measured at the metacarpophalangeal joint line of the open hand).

| Subject | Gender (m/f) | Stature/height (cm) | Weight (kg) | Hand length (mm) | Hand breadth (mm) | Hand circumference (mm) |
|---------|--------------|---------------------|-------------|------------------|-------------------|-------------------------|
| 1 | m | 177.8 | 85.2 | 183 | 85 | 209 |
| 2 | m | 186.7 | 90.8 | 195 | 100 | 225 |
| 3 | m | 188.0 | 125.2 | 210 | 95 | 231 |
| 4 | m | 185.4 | 86.2 | 182 | 87 | 205 |
| 5 | m | 177.8 | 104.0 | 188 | 87 | 210 |
| 6 | m | 177.8 | 76.2 | 188 | 90 | 214 |
| 7 | m | 182.9 | 110.0 | 190 | 90 | 220 |
| 8 | m | 175.0 | 73.8 | 192 | 90 | 210 |
| 9 | m | 193.0 | 106.6 | 205 | 89 | 219 |
| 10 | m | 177.8 | 87.0 | 200 | 89 | 212 |
| Mean | | 182.2 | 94.5 | 193 | 90 | 216 |
| SD | | 5.9 | 16.4 | 9 | 4 | 8 |



Fig. 6. Jamar dynamometer handle and grip posture with the handle span set at its second narrowest setting (47.6 mm) for simulating the 40 mm cylindrical handle grip.

gle is shown in Fig. 6. The sequence of trials on the Jamar handle and the cylindrical handle were fully randomized.

2.5. Statistical analysis of the experimental data

Wherever applicable, linear correlations between pairs of data were examined, and the calculated correlation coefficients (r -values) and statistical probabilities (p -values) were used to assess the reliability of the relationships. Also wherever applicable, paired two-tailed t -tests were performed to assess the significance of the difference between pairs of data. Differences were considered significant at $p \leq 0.05$.

3. Experimental results

3.1. Calibration results

An arm from each of the three handle structures was tested for linearity along its length. The force measurements with the eight-arm and ten-arm structures were found to be location-specific, as shown in Fig. 7(a and b). The maximum difference was more than 23% of the applied load for the ten-arm handle and more than 17% for the eight-arm handle. Therefore, further developments and tests of these two handles were discontinued for this study.

As shown in Fig. 7(c), the force measurement with the six-arm structure is practically independent of the load location. An error of less than 4% was found at the end of the arm furthest away from the strain gauges. As shown in Fig. 8, the measurement on each of the six arms is highly linear ($r \geq 0.999$, $p < 0.001$) in the calibrated force range (11.3–333.6 N). The six-arm handle was thus selected for further developments and experiments.

3.2. Grip strength

As an example, Fig. 9 shows the typical distribution of the grip strength components on the six arms, which was measured in the first experiment with a subject. The highest normal force was recorded on Arm 5 where the fingertips are positioned in the gripping action (see Fig. 5(c)). The second highest force was measured on Arm 2, which is in direct opposition to Arm 5. The lowest force was recorded on Arm 6 where the hand has the least contact with the handle.

Fig. 10 shows the average distribution of the grip force on the six arms, which was measured in the second experiment with ten subjects. Consistent with that observed in Fig. 9, whereas the grip

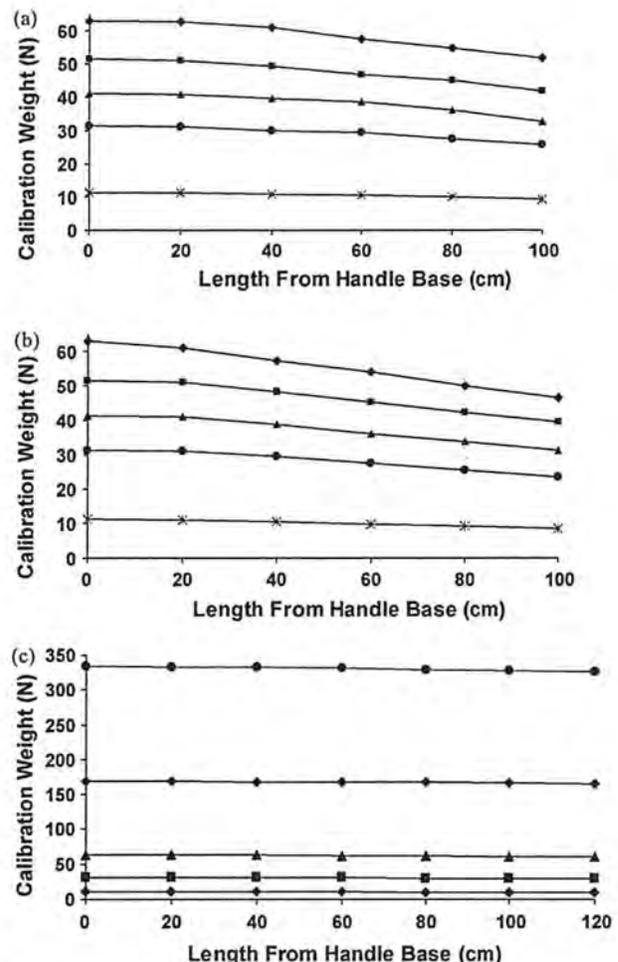


Fig. 7. Calibration data for a single arm: (a) the eight-arm handle; (b) the ten-arm handle; and (c) the six-arm handle (eight-arm and ten-arm handles only used up to 63.1 N weight due to deflection when weight was placed at end of the arm).

force (mean = 207 N; SD = 45 N) on Arm 5 is reliably greater than that on any other arm ($p < 0.001$), the grip force on Arm 6 is the lowest (mean = 57 N; SD = 21 N) ($p < 0.001$). Inconsistent with that shown in Fig. 9, the second largest force (mean = 180 N; SD = 37 N) is on Arm 1, but it is not reliably different ($p = 0.471$) from that on Arm 2 (mean = 175 N; SD = 40 N), which suggests that the grip forces distributed on each of these two arms are similar. As expected, the grip forces distributed on the six arms are reliably correlated with each other ($r \geq 0.402$, $p < 0.028$), except that the correlation between the forces on Arms 1 and 6 is poor ($r = 0.173$, $p = 0.361$). Also as expected, the forces on Arms 1 and 4 and those on Arms 2 and 5 are highly correlated ($r \geq 0.848$, $p < 0.001$), which are the arms opposite of one another where the large force values are observed.

Table 3 contains data for comparing the grip strengths measured with the cylindrical handle and the Jamar handle in the second experiment. The Jamar grip strength is significantly less than that measured with the multi-arm cylindrical handle ($p < 0.001$). This is primarily because the Jamar handle only measures a portion of the grip force. The correlation analysis also indicates that these two grip strengths are poorly correlated ($r = 0.263$, $p = 0.463$).

3.3. Effect of friction force

Table 4 lists the grip strength values measured in the first experiment, together with the differences between the forces on opposing halves of the handle in three different orientations, which were

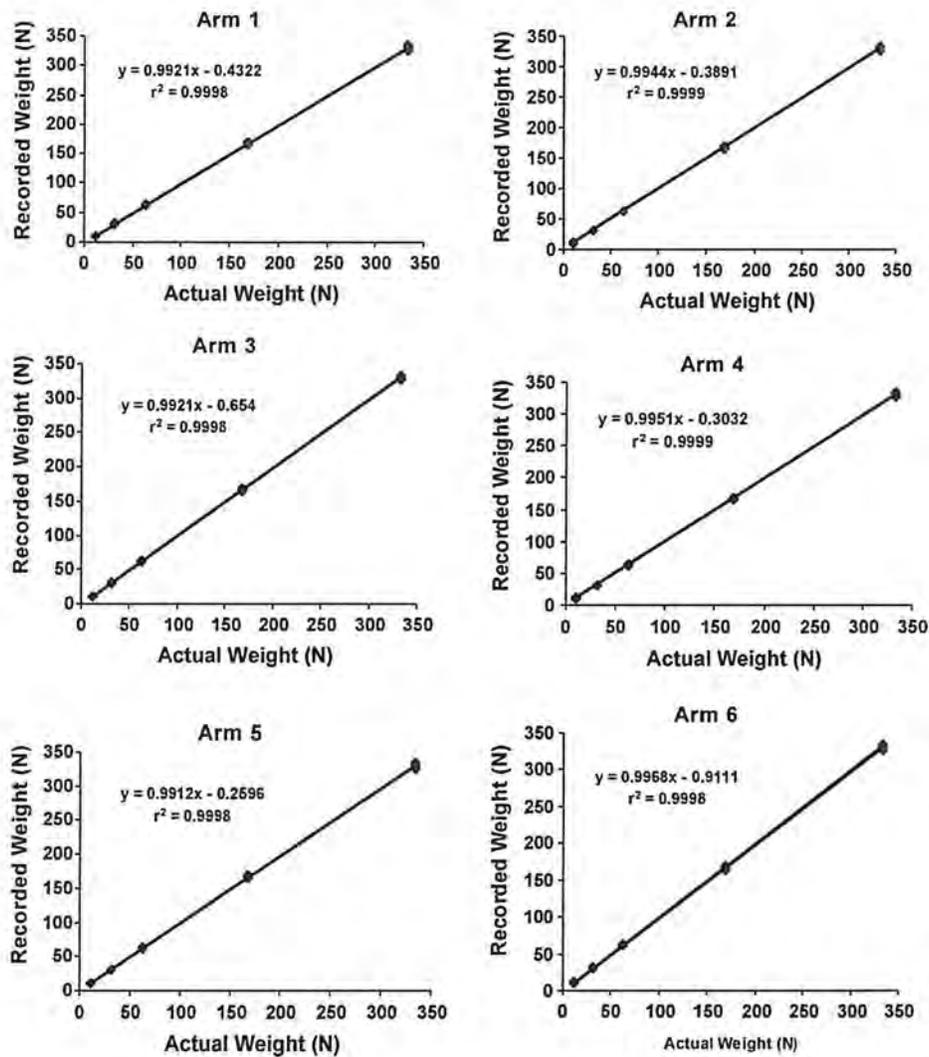


Fig. 8. Regression of the calibration data of the six-arm handle.

calculated using Eqs. (5)–(7). The coefficient of friction measured with the bare hand (mean = 0.36; SD = 0.05) is less than that measured with the hand wearing a latex glove (mean = 0.64; SD = 0.04) ($p < 0.001$). There is no significant difference between the grip strengths (Table 4) measured with these two hand treatments ($p = 0.773$). The average percent differences between the forces on

opposing halves in these two hand treatments are also similar: approximately 9% for the bare hand and 10% for the gloved hand, and they are not statistically different ($p = 0.565$).

However, the oiled hand grip strength is less than ($p \leq 0.001$) those measured with other two hand treatments (Table 4). This is because the μ -value of the oiled hand (mean = 0.11; SD = 0.01) is greatly reduced. Also because of the μ -value reduction, the average percent difference between the forces on opposing halves is only 2.6% for the oiled hand treatment.

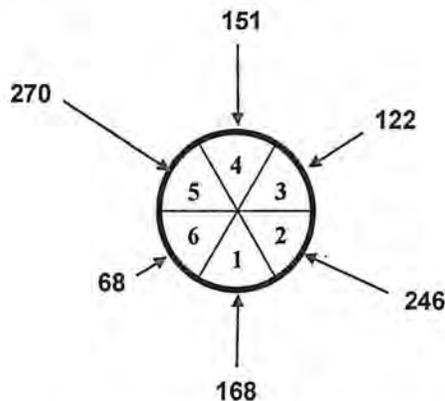


Fig. 9. An example of the normal force distribution measured on the six arms when a subject applied the maximum grip force with a bare hand in the first experiment.

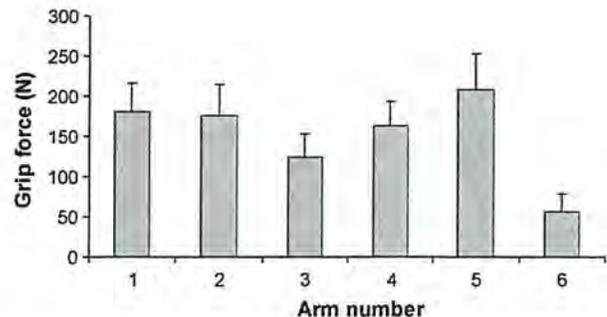


Fig. 10. The average grip strength distributed on the six arms measured with a bare hand of the ten subjects in the second experiment.

Table 4
Comparison of grip strength measured with the Jamar handle and cylindrical handle.

| Subject | Jamar (N) | Cylindrical (N) |
|---------|-----------|-----------------|
| 1 | 490 | 986 |
| 2 | 585 | 779 |
| 3 | 533 | 679 |
| 4 | 584 | 909 |
| 5 | 454 | 763 |
| 6 | 621 | 841 |
| 7 | 631 | 1061 |
| 8 | 556 | 1188 |
| 9 | 588 | 982 |
| 10 | 575 | 870 |
| Mean | 562 | 906 |
| SD | 56 | 153 |

4. Discussion

A new dynamometer was developed in this study to measure the grip strength applied on a 40 mm cylindrical handle. The theoretical analyses and experimental results provide useful information for understanding the multi-arm handle measurement method and its applications.

4.1. Grip force distribution

Previous studies suggested that the majority of force applied by an individual's finger is observed at the distal phalange (fingertip) region of the fingers [14,18,22], and the direction of the principal grip force is approximately along the line that connects the handle center to the center of the fingertip contact position [16]. These observations are consistent with the findings of the current study. This suggests that a more consistent and representative measurement can be achieved by positioning the fingertip center area at the center of an arm in each trial for every subject.

Because the fingertips are not positioned on the plane of measurement of the Jamar handle for the handle dimension used in this study, as shown in Fig. 6, the fingertip cannot be fully

taken into account in the measurement with the Jamar handle. This at least partially explains why the grip strength measured with the Jamar handle is poorly correlated with that measured with the cylindrical handle. Further reducing the grip span on the Jamar handle makes the fingertip alignment worse, which could possibly make their correlation even poorer. However, when the Jamar handle span is increased to a certain extent, the fingertip area will become more aligned with the measurement plane. In such a case, the grip strengths measured with these two methods may become reliably correlated. Therefore, it is anticipated that their correlation depends on the handle size used in the measurement.

For a given grip span on the Jamar handle, the position of the fingertips on the handle varies with the finger/hand length. Because the position of the fingertips on the handle is important to the measurement result, the hand length is a confounding factor in the measurement. This confounding factor can be largely avoided using the cylindrical dynamometer developed in this study because its measurement is much less sensitive to the fingertip location on the handle.

If the fingertips are positioned in the same measurement plane for both the Jamar and cylindrical handles, on any given size handle, the grip strength data may correspond to one another. For instance, a 40 mm cylindrical handle might correspond to a Jamar handle setting larger than 40 mm so that the fingertips are in the same measurement plane. This measurement approach may make the Jamar grip strength data generally applicable to the cylindrical handle when a reliable relationship between these two grip strengths, for each given handle dimension, is established. This approach, however, will greatly change the grip posture when using small spans on the Jamar handle. The shapes of the current Jamar handles are also not designed for such a grip posture.

More than 60% of the grip strength is provided by the index and middle fingers [18,23]. With the grip posture shown in Fig. 5(a), these fingers are positioned in the upper measurement zone nearest to the strain gauges where little location-related error was observed during the calibration (see Fig. 7). Therefore, it is recommended to apply this hand/handle grip orientation for strength measurements.

Table 3

Grip strength values measured for six subjects with bare hand, hand wearing a latex glove, and oiled hand. O_I = Orientation 1, O_{II} = Orientation 2, and O_{III} = Orientation 3, as defined by Fig. 4.

| | Subject | | | | | | Mean grip strength |
|---------------------------------|---------|--------|-------|--------|-------|-------|--------------------|
| | 1 | 2 | 3 | 4 | 5 | 6 | |
| Bare hand | | | | | | | |
| Mean | 1026.4 | 1256.7 | 544.8 | 1079.3 | 559.6 | 441.5 | 818.0 |
| CV | 0.334 | 0.272 | 0.630 | 0.318 | 0.612 | 0.776 | 0.490 |
| Difference (%) | | | | | | | |
| O_I | 6.0 | 14.0 | 6.8 | 6.0 | 9.3 | 6.4 | 8.1 |
| O_{II} | 13.1 | 10.9 | 10.9 | 8.5 | 12.4 | 10.5 | 11.6 |
| O_{III} | 24.6 | 5.2 | 3.1 | 1.9 | 1.9 | 2.9 | 6.6 |
| Hand wearing latex glove | | | | | | | |
| Mean | 1072.9 | 1327.1 | 532.8 | 973.7 | 617.1 | 429.3 | 825.5 |
| CV | 0.328 | 0.266 | 0.661 | 0.362 | 0.571 | 0.820 | 0.501 |
| Difference (%) | | | | | | | |
| O_I | 3.0 | 9.3 | 7.6 | 8.2 | 12.4 | 5.0 | 7.6 |
| O_{II} | 17.1 | 10.2 | 15.4 | 10.8 | 11.6 | 16.0 | 13.5 |
| O_{III} | 24.2 | 0.1 | 6.2 | 2.0 | 2.2 | 9.1 | 7.3 |
| Oiled hand/handle | | | | | | | |
| Mean | 900.1 | 927.0 | 523.2 | 851.5 | 604.7 | 356.5 | 701.3 |
| CV | 0.270 | 0.250 | 0.465 | 0.285 | 0.402 | 0.682 | 0.392 |
| Difference (%) | | | | | | | |
| O_I | 2.5 | 5.0 | 3.3 | 1.8 | 0.4 | 2.4 | 2.6 |
| O_{II} | 3.4 | 2.1 | 3.2 | 1.1 | 1.1 | 3.0 | 2.3 |
| O_{III} | 7.1 | 3.6 | 0.6 | 2.8 | 1.3 | 0.2 | 2.6 |

4.2. Effects of friction force

The results listed in Table 3 confirm that some friction force exists during the grip-only exertion or action. The grip strength values for the bare hand and the latex glove (no oil) were found to be very similar, which suggests the thickness of the glove and the difference between their coefficients of friction did not significantly influence the grip strength. Therefore, the reduction of the grip strength in the oiled glove and handle must result from the presence of the oil. Because the same hand and arm postures were applied in all the tests and the effect of the latex glove thickness can be ignored, the normal pressure distribution was unlikely to be significantly changed in any of the three testing treatments. The presence of the oil reduced the percent difference between the grip forces on the two halves from about 9% to about 2.6%. These observations suggest that the contribution of the asymmetric distribution of the normal force to tangential force on the 40 mm six-arm handle is less than that of the friction force. These findings suggest that the friction force can stabilize the grip action by limiting movement of the handle and marginally increasing the grip strength. This also suggests that it is useful to keep the hand dry and clean in the use of a tool, even if there is no significant reacting torque in the operation (such as would be found while using a chipping hammer, for instance).

As revealed in Eq. (1), the friction force is partially taken into account in the normal force measurement with the multi-arm handle. Primarily because of the friction force, the normal force measured on one half of the handle is generally not equal to that of the opposing half. This phenomenon has been reported previously [16] and experimentally confirmed in the current study (Table 3). However, with oil applied to the handle and glove, the friction force is dramatically reduced. As a result, the tangential force on each arm becomes practically negligible. In such a case, the normal forces on the handle should be balanced; the difference between the forces on any opposing handle halves should be very small. This is realized in this study, as indicated in the results listed in Table 3. This observation also suggests that the handle developed in the current study is sufficiently accurate for the measurement of grip strength – with respect to friction adding slightly to the overall grip strength.

It was also of concern that skin could penetrate into the 1 mm gaps between the arms, reducing the accuracy in the measurements due to added or reduced tangential forces. The use of a latex glove would likely prevent or reduce the potential for skin penetration. However, in the present study, use of the latex glove did not significantly affect the grip strength or the percent difference between the grip forces on two halves of the handle. Furthermore, subjects would likely feel a pinching effect if skin were to penetrate into the gaps during the gripping action. None of the subjects reported any pinching sensations during the experiments. Therefore, this is unlikely to be a significant factor affecting the accuracy of the measurements with this instrumented handle.

4.3. Handle structure

Increasing the number of the arms in the handle structure can provide more information on the distribution of the grip strength, and to an extent allow a higher percentage of the normal contact force to be measured (theoretically predicted in Section 2.3). However, the calibration results also suggest that it is difficult to obtain a load location-independent measurement with the 40 mm eight- and ten-arm handles. This is because the distribution pattern of the measured shear strain could be affected by the size of the arm. Increasing the number of arms lessens the arm stiffness and strength. To avoid contact between any two arms during a grip action, the reduced stiffness may require increasing the gap size,

which will increase the gap effect. Moreover, increasing the number of arms also increases the number of gaps around the handle, which will further increase the gap effect. Increasing the number of arms also increases the cost of the handle fabrication and instrumentation. The results of this study suggest that the six-arm handle is sufficient for quantifying the grip effect on a 40 mm handle.

4.4. Possible extensions of the handle applications

The 40 mm instrumented handle developed in this study can also be used to measure the pinch force or pinch strength. It is also possible to use the 40 mm handle to measure the pinch and grip strengths applied on a larger handle size by attaching a cap on each arm to increase the effective diameter of the handle. This approach, however, may only be acceptable in a certain size range. If the handle circumference is too large to be fully covered by the hand, some arms may become loaded off-center, and the measurements from such arms may not closely reflect the actual contact force applied on that arm. A higher level of friction force may appear when the handle size is greater than 80 mm [18]. The measured grip strength may thus largely depend on the grip orientation, similar to that measured with the conventional two-arm handle [15,16]. Further studies are required to determine the extent of handle sizes feasible using the methods developed in this study to accurately measure grip force and strength.

5. Conclusions

This six-arm cylindrical dynamometer developed in this study proved to be suitable for determining the overall grip strength of a subject, as well as showing the grip distribution around the surface of the handle. The calibration results show that the potential maximum percent error is less than 4%. The dynamometer demonstrated that the grip measurement was independent of the hand's longitudinal placement along the dynamometer. The experimental results suggest that the developed dynamometer is suitable for measuring grip strength with sufficient accuracy and repeatability for some clinical applications.

This study confirmed that some friction force exists in the grip action, but its level is small when compared to the normal force. The friction force is partially taken into account in the measurement with the multi-arm handle. This study also found that the friction force can stabilize the grip action and marginally increase the grip strength. Therefore, it is useful to keep the hand dry and clean in gripping actions.

The grip strengths measured with the 40 mm cylindrical handle and the Jamar handle with a 47.6 mm span are poorly correlated. This suggests that the grip strength measured with the Jamar handle may not be reliably applicable to the designs and risk assessments of tools or machines with cylindrical handles in this size range.

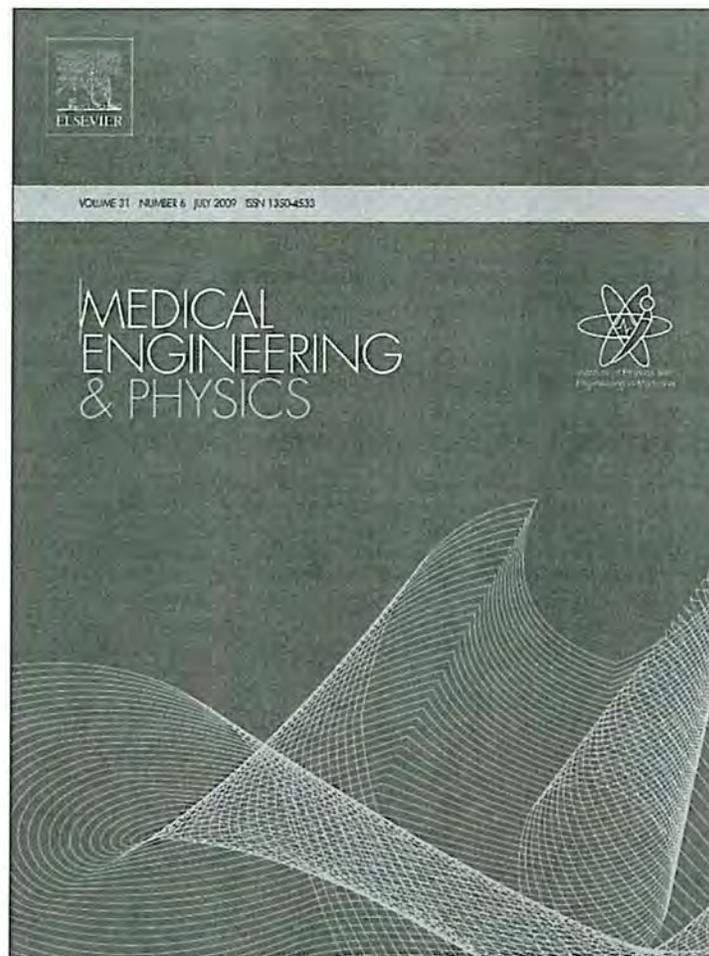
Conflict of interest

None of the authors have any financial or personal relationships with people or organizations that could inappropriately influence (bias) our work.

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